Joint UL/DL Resource Allocation for UAV-Aided Full-Duplex NOMA Communications

Wenjuan Shi, *Member, IEEE,* Yanjing Sun, *Member, IEEE,* Miao Liu, *Member, IEEE,* Hua Xu, *Member, IEEE,* Guan Gui, *Senior Member, IEEE,* Tomoaki Ohtsuki, *Senior Member, IEEE,* Bamidele Adebisi, *Senior Member, IEEE,* Haris Gacanin, *Fellow, IEEE,* and Fumiyuki Adachi, *Life Fellow*, *IEEE*

***Abstract*—This paper proposes an unmanned aerial vehicle (UAV)-aided full-duplex non-orthogonal multiple access (FD-NOMA) method to improve spectrum efficiency. Here, UAV is utilized to partially relay uplink data and achieve channel differentiation. Successive interference cancellation algorithm is used to eliminate the interference from different directions in FD-NOMA systems. Firstly, a joint optimization problem is formulated for the uplink and downlink resource allocation of transceivers and UAV relay. The receiver determination is performed using an access-priority method. Based on the results of the receiver determination, the initial power of ground users (GUs), UAV, and base station is calculated. According to the minimum sum of the uplink transmission power, the Hungarian algorithm is utilized to pair the users. Secondly, the subchannels are assigned to the paired GUs and the UAV by a message-passing algorithm. Finally, the transmission power of the GUs and the UAV is jointly fine-tuned using the proposed access control methods. Simulation results confirm that the proposed method achieves higher performance than state-of-the-art orthogonal frequency division multiple-access method in terms of spectrum efficiency, energy efficiency, and access ratio of the ground users.**

***Index Terms*—Unmanned aerial vehicle, full-duplex, non-orthogonal multiple access, message passing, resource allocation.**

I. INTRODUCTION

The fifth-generation (5G) mobile network is being standardized and deployed worldwide starting in 2020, supporting three major communication scenarios, i.e., enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low latency communications (uRLLC) [1]. How to improve spectral efficiency is one of the critical tasks in beyond 5G (B5G) and sixth-generation (6G) wireless communications [1]. In recent years, both full-duplex (FD) [2] and non-orthogonal multiple access (NOMA) [3] technologies are considered as potential techniques to improve the spectral efficiency. The FD can simultaneously transmit and receive signals on the same channel at the same frequency. With recent advances in self-interference cancelation (SIC[1]) technology [4–6], the spectral efficiency of the FD mobile networks can theoretically be double of the traditional half-duplex networks. Therefore, FD has been regarded as a candidate technology for implementing future wireless systems. In a parallel development, NOMA can serve multiple users simultaneously by superimposing the signals of users at the same frequency while at different power levels [7, 8]. M. Elbamby *et al*. [9] demonstrated FD-NOMA with resource optimization and power allocation to achieve a high throughput in an ultra-dense network. L. Wang *et al.* [10] presented user association and resource allocation in FD hybrid NOMA (FDH-NOMA) system, which can increase the sum rate of Internet of Thing (IoT) networks. Recent works in the literature show that both NOMA and FD techniques can coexist well and their combination can significantly improve spectrum efficiency [10].

With the advantages of providing line-of-sight (LoS) channel links with ground users (GUs) and the ability of rapid and flexible deployment, unmanned aerial vehicles (UAVs) have been widely used recently as a relay in wireless networks to improve system performance [11, 12]. Despite the promising performance of UAVs, the improvement of robust scheduling strategies remains a challenge in UAV-based cellular networks [13]. In [14, 15], UAVs were utilized as a relay for wireless communications between ground terminals to improve energy efficiency and system throughput. Since UAV-assisted traditional networks are limited by spectrum resources, mobile networks that integrate UAVs with NOMA [16–18] or UAVs with FD [19, 20] were proposed to improve the spectrum efficiency.In addition, many resource allocation methods [22] have been comprehensively introduced.

Moreover, in [21, 23], a UAV-enabled non-orthogonal multiple access (NOMA) system is investigated, in which the UAV acted as an FD relay to help the communication between the BS and NOMA users. In our previous work [24],

This work was supported by the Project Funded by the National Natural Science Foundation of China under Grant 61771417 and 62101283, the scientific research project of Yancheng Teacher University under Grant 12YCKL002, the JSPS KAKENHI under Grant JP19H02142, the Summit of the Six Top Talents Program of Jiangsu under Grant XYDXX-010, China Postdoctoral Science Foundation 2021M692409. (*Corresponding authors: Hua Xu*)

S. Shi and H. Xu are with the College of Physics and Electronic Engineering, Yancheng Teacher University, Yancheng 224002, China (e-mail: shiwj@yctu.edu.cn, xuhua@yctu.edu.cn).

Y. Sun is with the School of Information and Control Engineering, China University of Mining and Technology, Xuzhou 221116, China (e-mail: yjsun@cumt.edu.cn).

M. Liu and G. Gui are with the College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210003, China (e-mail: liumiao@njupt.edu.cn, guiguan@njupt.edu.cn).

T. Ohtsuki is with the Department of Information and Computer Science, Keio University, Yokohama 223-8521, Japan (e-mail: ohtsuki@ics.keio.ac.jp).

B. Adebisi is with the Department of Engineering, Faculty of Science and Engineering, Manchester Metropolitan University, Manchester M1 5GD, United Kingdom (e-mail: b.adebisi@mmu.ac.uk).

H. Gacanin is with the Faculty of Electrical Engineering and Information Technology, RWTH Aachen University, Aachen 55-52062, Germany (e-mail: harisg@ieee.org).

F. Adachi is the Research Organization of Electrical Communication, Tohoku University, Sendai 980-8577 Japan (e-mail: adachi@ecei.tohoku.ac.jp).

a distributed successive interference cancellation (SIC[2])-free NOMA scheme was proposed for UAV-assisted emergency communication in a heterogeneous IoT to increase the sum rate of the GUs and the access ratio (AR) of the devices. In our previous work [25], a UAV-aided air-to-ground cooperative NOMA scheme was proposed, and joint resource allocation was investigated to improve the spectrum efficiency. Different from the above literatures, in order to improve the spectral efficiency, we consider the application of NOMA and FD to not only the UAV, but also GU and BS.

In this paper, we propose a high efficient UAV-aided FD-NOMA method to improve the spectral efficiency in the UAV-aided FD-NOMA communication systems. The main contributions of this paper are summarized as below.

- A UAV-aided FD-NOMA system is introduced, in which a UAV hovers above the cell center to relay a partial UL stream. In particular, all the devices operate in the FD-NOMA mode. Moreover, through air-to-ground co-channel interference suppression, we pair the user-to-UAV and user-to-BS ULs on the same subchannels with high spectrum efficiency. In contrast, in the DL, the corresponding BS-to-user DLs can be paired on the same subchannels of ULs; both approaches can improve the spectrum efficiency.
- We use SIC[2] technology in NOMA to eliminate the interference from different directions in the FD system to simplify the system model, and double the spectral efficiency of the FD.
- A mixed-integer non-deterministic polynomial-time (NP)-hard optimization problem is derived for the proposed FD-NOMA scheme, considering both UL/DL issues on choosing receiver, pairing user, allocating power, and assigning subchannel. In addition, the constraints of the transmission and the signal-to-interference-and-noise ratios (SINR) are considered for the UAV, the GUs, and the BS.
- A joint UL/DL stepwise optimization scheme is proposed to solve the NP-hard optimization problem, which we simplify to several sub-problems through receiver determination, user pairing, power allocation, and subchannel assignments.

II. System Model

A model of UAV-aided FD-NOMA wireless cell is illustrated in Fig. 1. The BS is located at a center of a cell, and N users are randomly distributed in the coverage area of the cell. All the GUs and the BS are employed with FD communication technology. In the above cell, all the GUs and the BS operate on the FD-NOMA scheme. The achievable spectrums are equally divided into F_T subchannels. The unit bandwidth of these subchannels is set as B_0. The UAV is deployed to relay partial UL stream from the GUs for lower power consumption and higher data rate. In this paper, it is assumed that the UAV relays data using a decode-and-forward scheme, and perfect SIC[1] is assumed. In addition, based on our previous work [25], it has been verified that by utilizing UAV relay for the UL, the GUs' power can be significantly saved with lower cochannel interference. Due to the energy limitation of the UAV, it is only used as the relay in the uplink, while the BS sends the DL signals directly to the GUs. Additionally, the aerially relayed and directly transmitted signals in the UL are superimposed on the same subchannels to improve the spatial efficiency and energy efficiency, whereas the DL signals transmitted from the BS to the GUs are superimposed on the same subchannels.The list of symbols is given in Table I.

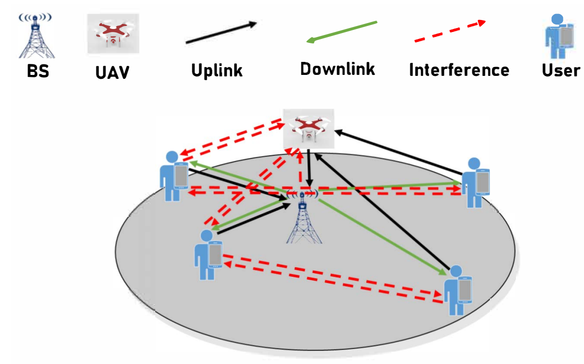

Fig. 1. The model of the UAV-aided FD-NOMA wireless cellular network.

In the UL, the channels from the GUs to the UAV are the ground-to-air (G2A) links. Referred to [25–27], the G2A channel model is defined as

$$G_{i,U}^{\mathrm{G2A}} = \left\{ \begin{array}{l} \eta^{\mathrm{LoS}} d_{i,U}^{-\alpha_{\mathrm{A}}} \\ \eta^{\mathrm{NLoS}} d_{i,U}^{-\alpha_{\mathrm{A}}} \end{array} \right. , \quad (1)$$

where η^{LoS} and η^{NLoS} are additional attenuation factors of the LoS and NLoS channels, respectively. $d_{i,U}$ is the distance between the i-th GU and the UAV, α_{A} is the path loss factor of the G2A channels. According to [25, 28, 29], the LoS probability of the i-th GU with the G2A channel is

$$p_{i,U}^{\mathrm{LoS}} = \frac{1}{1+\psi \exp\left(-\beta\left[\theta_{i,U}-\psi\right]\right)}, \quad (2)$$

where β and ψ are constants related to the system environment, respectively. Additionally, $\theta_{i,U}$ is the elevation angle (measured in degrees) from the i-th GU to the UAV relay, expressed as $\theta_{i,U} = \arcsin(H_U/d_{i,U})$, and H_U is the hovering height of the UAV. Since the UAV is assumed to be always hovering above the BS, the LoS probability of the link between the UAV and the BS is assumed to be 1 [24, 25]. The power gain for the transmitting link between the BS and the UAV can be expressed as $G_{U,B}^{\mathrm{RE}} = \eta^{LoS} H_U^{-\alpha_{\mathrm{A}}}$. Moreover, the height of the BS can be negligible compared to the UAV's height. Therefore, the direct links between the BS and the GUs are ground-to-ground (G2G) is modeled as $G_{i,B,f}^{\mathrm{G2G}} = d_{i,B}^{-\alpha_{\mathrm{G}}} |h_f|^2$, which denotes the power gain for the transmitting link from the i-th GU and the BS on subchannel f, where $d_{i,B}$ represents the distance between the BS and the i-th GU, α_{G} is the path loss factor of the G2G channel, and h_f is the amplitude gain of the signals on subchannel f.

Due to the battery-power limitation of the UAV, in the DL, the BS directly transmits data to the GUs without the UAV. $G_{B,i,f}^{\mathrm{G2G}}$ denotes the power gain for the G2G transmitting link between the i-th GU and the BS on subchannel f, and its

TABLE I
LIST OF SYMBOL AND ITS DEFINITION.

Symbol	Definition
B_0	The bandwidth of the subchannel
i,j	Index of GU
$d_{i,U}$	Distance between the i-th GU and the UAV
$d_{i,B}$	Distance between the BS and the i-th GU
$d_{i,j}$	Distance between the i-th and the j-th GU
h_f	Amplitude gain of the signals on subchannel f
N_0	The bandwidth of the subchannel
$x^{\mathrm{U}}_{i,f}$, $y^{\mathrm{B}}_{i,f}$	Binary variables determined by the results of the receiver and subchannel assignment for the i-th GU
Z_0	The additive white Gaussian noise
α_{A}, α_{G}	the path loss factor of the G2A and G2G channels
ψ,β	Constants related to the system environment
$\theta_{i,U}$	Elevation angle from i-th GU to UAV relay
η^{LoS}, η^{NLoS}	Attenuation factors of the LoS and NLoS channels
F_i	Minimum number of subchannels required by the i-th GU
$AP_i^{\mathrm{U/B}}$	The priorities for the receiver determination of the i-th GU
$p^{\mathrm{LoS}}_{i,U}$	LoS probability of i-th GU with G2A channel
$G^{\mathrm{G2A}}_{i,U}$	Power gain of G2A channel from i-th GU to UAV
$G^{\mathrm{RE}}_{U,B}$	Power gain for transmitting link between UAV and BS
$G^{\mathrm{G2G}}_{i,B,f}$, $G^{\mathrm{G2G}}_{B,i,f}$	Power gain for transmitting link between i-th GU and BS on subchannel f
$g^{\mathrm{G2G}}_{i,j,f}$	Power gain for G2G interference between i-th GU and j-th GU on subchannel f
$P^{\mathrm{U}}_{B,i,f}$, $P^{\mathrm{B}}_{B,j,f}$	DL power of the BS to i-th and j-th GU on subchannel f, respectively
$P^{\mathrm{G2A}}_{i,U,f}$, $P^{\mathrm{G2G}}_{j,B,f}$	UL power of i-th and j-th GU on subchannel f, respectively
$P^{\mathrm{RE}}_{i,f}$	Relay power of UAV to BS
P_i^{UL}, P_i^{DL}	Consumed power budget of i-th GU in UL and DL, respectively
P^{UL}, P^{DL}	Consumed power budget of GU in UL and DL, respectively
$P_i^{\mathrm{UL}*}$, $P_i^{\mathrm{DL}*}$	Maximum power budget of i-th GU in UL and DL, respectively
$P^{\mathrm{IJW}}_{i,f}$	Power sum of paired GUs on subchannel f in UL/DL
$R^{\mathrm{G2G}}_{B,i,f}$, $R^{\mathrm{G2G}}_{B,j,f}$	Subchannel capacity from BS to i-th and j-th DL GU on subchannel f, respectively
$R^{\mathrm{RE}}_{i,f}$	Subchannel capacity from UAV to BS on subchannel f
$R^{\mathrm{G2A}}_{i,U,f}$, $R^{\mathrm{G2G}}_{j,B,f}$	UL capacity from i-th and j-th UL GU on subchannel f, respectively
$R_i^{\mathrm{UL}*}$, $R_i^{\mathrm{DL}*}$	Minimum total sum rate of i-th GU in UL and DL, respectively
$x^{\mathrm{DL}}_{GU_i}$, $x^{\mathrm{DL}}_{GU_j}$	G2G message from BS to i-th and j-th GU, respectively
$x^{\mathrm{UL}}_{GU_i}$, $x^{\mathrm{UL}}_{GU_j}$	G2G message from i-th and j-th GU in UL, respectively
$x^{\mathrm{UL}}_{\mathrm{UAV}}$	A2G UL interference from UAV
$x^{\mathrm{DL_i}}_{GU}$, $x^{\mathrm{UL_j}}_{GU}$	FD introduced DL self-interference for i-th and j-th DL GU, respectively
$y^{\mathrm{DL}}_{GU_i}$, $y^{\mathrm{UL}}_{GU_j}$	Original received signal of i-th and j-th DL GU, respectively
$y^{\mathrm{UL}}_{\mathrm{UAV}}$, $y^{\mathrm{UL}}_{\mathrm{BS}}$	Received signal of UAV and BS, respectively
$\gamma^{\mathrm{G2G}}_{B,i,f}$, $\gamma^{\mathrm{G2G}}_{B,j,f}$	DL SINR of i-th and j-th GU on subchannel f, respectively
$\gamma^{\mathrm{UL}}_{i,U,f}$, $\gamma^{\mathrm{UL}}_{j,B,f}$	UL SINR of i-th and j-th GU on subchannel f, respectively
$\gamma^{\mathrm{RE}}_{i,f}$	UL SINR of UAV on subchannel f
$\gamma^{\mathrm{UL}}_{i,f}$, $\gamma^{\mathrm{DL}}_{i,f}$	UL and DL SINR of i-th GU on subchannel f, respectively
$\gamma^{\mathrm{UL}*}_{i,f}$, $\gamma^{\mathrm{DL}*}_{i,f}$	Minimum SINR of i-th GU in UL and DL, respectively

expression is the same as the definition of $G^{\mathrm{G2G}}_{i,B,f}$ above. $g^{\mathrm{G2G}}_{i,j,f}$ is the power gain for the G2G interference between the i-th GU and the j-th GU on subchannel f, expressed as $g^{\mathrm{G2G}}_{i,j,f} = d_{i,j}^{-\alpha_{\mathrm{G}}}|h_f|^2$, where $d_{i,j}$ is the distance between the i-th and j-th GUs.

III. Interference Cancelation

According to the above channel models introduced in Section II, the i-th and j-th GUs are assumed to be accommodated on subchannel f, both in the UL/DL. In the UL, we assume that the j-th GU is directly assigned to the BS, and the i-th GU is assigned to the UAV relay. In the DL, the i-th GU can receive not only the DL G2G message from the BS, but also the UL interference from the UAV to the BS, the G2G DL interference from the BS to the j-th GU, the G2G UL interference from the j-th GU to the BS, its UL self-interference, and the noise. The original received signal $y^{\mathrm{DL}}_{GU_i}$ of the i-th DL GU contains the FD introduced UL self-interference, the A2G UL interference from the UAV, the G2G message from the BS, the G2G DL interference from the BS, the G2G UL interference from the j-th GU and the noise. It can be expressed as

$$\begin{aligned} y^{\mathrm{DL}}_{GU_i} = &\sqrt{G^{\mathrm{G2G}}_{B,i,f}P^{\mathrm{U}}_{B,i,f}}x^{\mathrm{DL}}_{GU_i} + \sqrt{g^{\mathrm{G2G}}_{i,j,f}P^{\mathrm{G2G}}_{j,B,f}}x^{\mathrm{UL}}_{GU_j} \\ &+ \sqrt{G^{\mathrm{G2A}}_{i,U}P^{\mathrm{RE}}_{i,f}}x^{\mathrm{UL}}_{\mathrm{UAV}} + \sqrt{G^{\mathrm{G2G}}_{B,i,f}P^{\mathrm{B}}_{B,j,f}}x^{\mathrm{DL}}_{GU_j} \\ &+ z_0 + I_s(x^{\mathrm{UL}}_{GU_i}) \end{aligned} \quad (3)$$

where $P^{\mathrm{U}}_{B,i,f}$ and $P^{\mathrm{B}}_{B,j,f}$ denote the DL power of the BS to the i-th and j-th GU on the subchannel f, respectively, $P^{\mathrm{G2G}}_{j,B,f}$ denotes the UL power of the jth GU to the BS on subchannel f, $P^{\mathrm{RE}}_{i,f}$ denotes the relay power of the UAV to the BS, $x^{\mathrm{DL}}_{GU_i}$ denotes the G2G message from BS to the i-th GU, $x^{\mathrm{UL}}_{GU_j}$ denotes the G2G UL interference from the j-th GU, x^{UL}_{UAV} denotes the A2G UL interference from the UAV, $x^{\mathrm{DL}}_{GU_j}$ denotes the G2G DL interference from BS, $x^{\mathrm{UL}}_{GU_i}$ denotes the FD introduced UL self-interference, z_0 denotes the additive white Gaussian noise, $I_s(\cdot)$ denotes the SIC^1 function of FD.

Since the channel from the UAV to the BS is the A2G link with LoS, the quality of the A2G channel is better than that of the G2G channel. Hence, the received signal strength (RSS) of the interference from the UAV for the i-th DL GU is always much stronger than that from the BS and other GUs. In the DL, based on the principle of the NOMA, the i-th DL GU, which is on the cell edge UL with the UAV need more transmission power from the BS than the j-th DL GU. Therefore, the RSS of G2G message from the BS to the i-th DL GU should be stronger than that of G2G DL interference from the BS to the j-th DL GU. For the j-th GU, the RSS from the BS is always stronger than the UL transmission signal strength. Thus, the RSS of the G2G DL interference from the BS is stronger than that of the G2G UL interference from the j-th UL GU.

Based on the above analysis in the DL, we utilize the SIC^1 of FD to cancel the strong self-interference, and then use the SIC^2 of NOMA to cancel the A2G UL interference from UAV. Thus, the DL SINR of the i-th DL GU on subchannel f can be expressed as

$$\gamma_{B,i,f}^{\mathrm{G2G}} = \frac{G_{B,i,f}^{\mathrm{G2G}} P_{B,i,f}^{\mathrm{U}}}{N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} P_{B,j,f}^{\mathrm{B}}}. \tag{4}$$

Based on the Shannon's capacity theorem, the subchannel capacity from the BS to the i-th DL GU on subchannel f can be obtained as

$$\begin{aligned} R_{B,i,f}^{\mathrm{G2G}} &= B_0 \log_2(1 + \gamma_{B,i,f}^{\mathrm{G2G}}) \\ &= B_0 \log_2 \left(1 + \frac{G_{B,i,f}^{\mathrm{G2G}} P_{B,i,f}^{U}}{N_0 B_0 + g_{i,j,f}^{G2G} P_{j,B,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} P_{B,j,f}^{\mathrm{B}}} \right) \end{aligned} \tag{5}$$

where N_0 denotes the power spectral density of the noise, B_0 denotes the bandwidth of the subchannels.

Similar analysis as the i-th DL GU, for the j-th DL GU, it can receive not only DL G2G message from the BS to the j-th GU, but also UL interference from the UAV to the BS, G2G DL interference from the BS to the i-th GU, G2G UL interference from the i-th GU to the UAV, its UL self-interference, and the noise. Thus, the original received signal $y_{GU_j}^{\mathrm{DL}}$ of the j-th DL GU contains the FD introduced UL self-interference, the A2G UL interference from the UAV, the G2G DL interference from the BS, the G2G message from the BS, the G2G UL interference from the i-th GU and the noise. It can be expressed as

$$\begin{aligned} y_{GU_j}^{\mathrm{DL}} = & \sqrt{G_{B,j,f}^{\mathrm{G2G}} P_{B,j,f}^{B}} x_{GU_j}^{\mathrm{DL}} + \sqrt{g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}} x_{GU_i}^{\mathrm{UL}} \\ & + \sqrt{G_{j,U}^{\mathrm{G2A}} P_{i,f}^{\mathrm{RE}}} x_{UAV}^{\mathrm{UL}} + \sqrt{G_{B,j,f}^{\mathrm{G2G}} P_{B,i,f}^{\mathrm{U}}} x_{GU_i}^{\mathrm{DL}} \\ & + z_0 + I_s(x_{GU_j}^{\mathrm{UL}}) \end{aligned} \tag{6}$$

where $x_{GU_j}^{\mathrm{DL}}$ is the G2G message from the BS, $x_{GU_i}^{\mathrm{UL}}$ is the G2G UL interference from the i-th GU, x_{UAV}^{UL} is the A2G UL interference from UAV, $x_{GU_i}^{\mathrm{DL}}$ is the G2G DL interference from the BS, $x_{GU_j}^{\mathrm{UL}}$ denotes the FD introduced UL self-interference.

Similar to the analysis for the i-th DL GU, the RSS of the interference from the UAV for the j-th DL GU is obviously much stronger than that from the BS and other GUs. In the DL, according to the analysis for the i-th DL GU, we observe that the RSS of the G2G DL message from the BS to the j-th DL GU is weaker than that of the G2G DL interference from the BS to the i-th DL GU. For the j-th GU, the DL RSS from the BS is always stronger than the UL transmission signal strength from each GU. Thus, the RSS of the G2G message from the BS is stronger than that of the G2G UL interference from the i-th GU. Similar to the i-th DL GU, for the j-th DL GU, the SIC^1 of FD is utilized to cancel the strong self-interference, and then the SIC^2 of NOMA is used to cancel the A2G UL interference from UAV and the G2G DL interference from the BS one by one. Thus, the DL SINR of the j-th DL GU on subchannel f can be given as

$$\gamma_{B,j,f}^{\mathrm{G2G}} = \frac{G_{B,j,f}^{\mathrm{G2G}} P_{B,j,f}^{\mathrm{B}}}{N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}} \tag{7}$$

Based on the Shannon's capacity theorem, the subchannel capacity from the BS to the j-th DL GU can be given as

$$\begin{aligned} R_{B,j,f}^{\mathrm{G2G}} &= B_0 \log_2 \left(1 + \gamma_{B,j,f}^{\mathrm{G2G}}\right) \\ &= B_0 \log_2 \left(1 + \frac{G_{B,j,f}^{\mathrm{G2G}} P_{B,j,f}^{\mathrm{B}}}{N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}} \right) \end{aligned} \tag{8}$$

where $P_{i,U,f}^{\mathrm{G2A}}$ denotes the UL power of the i-th GU to the UAV on subchannel f.

The original received signal y_{UAV}^{UL} of the UAV contains the FD introduced DL self-interference, the G2A DL interference from the BS to the i-th GU and the j-th GU, the G2A message from the the i-th GU to the UAV, the G2A UL interference from the j-th GU to the BS and the noise. It can be expressed as

$$\begin{aligned} y_{UAV}^{\mathrm{UL}} = & \sqrt{G_{i,U}^{\mathrm{G2A}} P_{i,U,f}^{\mathrm{G2A}}} x_{GU_i}^{\mathrm{UL}} + \sqrt{G_{U,B}^{\mathrm{RE}} P_{B,i,f}^{U}} x_{\mathrm{BS}}^{DL_i} \\ & + \sqrt{G_{U,B}^{\mathrm{RE}} P_{B,j,f}^{\mathrm{B}}} x_{\mathrm{BS}}^{DL_j} + \sqrt{G_{j,U}^{\mathrm{G2A}} P_{j,B,f}^{\mathrm{G2G}}} x_{GU_j}^{\mathrm{UL}} \\ & + z_0 + I_s(x_{UAV}^{\mathrm{DL}}) \end{aligned} \tag{9}$$

where $x_{GU_i}^{\mathrm{UL}}$ denotes the the G2A message from the i-th GU, $x_{BS}^{DL_i}$ denotes the G2A DL interference from the BS to the i-th DL GU, $x_{BS}^{DL_j}$ denotes the G2A DL interference from the BS to the j-th DL GU, $x_{GU_j}^{\mathrm{UL}}$ denotes the G2A UL interference from the j-th GU, x_{UAV}^{DL} denotes the FD introduced DL self-interference.

According to the analysis for the i-th DL GU and the j-th DL GU, the RSS of the G2A DL interference from BS to the i-th GU is much stronger than that of the G2A DL interference from BS to the j-th GU. It is well-known that the DL power from the BS to each GU is stronger than that of the UL transmission power from each GU to the BS [30], thus, the RSS of the G2A DL interference from BS to the j-th DL GU is stronger than the G2A messages from the i-th UL GU and the G2A UL interference from the j-th UL GU. In the UL, since the i-th UL GU is assigned to be UL with the UAV, the the channel quality from the i-th UL GU to the UAV must be better than that from the j-th UL GU to the UAV. Thus, the RSS of the message from the i-th UL GU to the UAV is much stronger than the G2A UL interference from the j-th GU.

Since the FD introduced DL self-interference is assumed to be canceled, after using the SIC^2 of NOMA to cancel the G2A DL interference from the BS to the i-th GU and the j-th GU, respectively. The G2A message from the i-th GU to the UAV can be decoded. Thus, the UL SINR of the UAV on subchannel f can be given as

$$\gamma_{i,f}^{\mathrm{RE}} = \frac{G_{i,U}^{\mathrm{G2A}} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,U}^{\mathrm{G2A}} P_{j,B,f}^{\mathrm{G2G}}}. \tag{10}$$

Based on the Shannon's capacity theorem, the subchannel capacity from the UAV to the BS on the subchannel f can be calculated as:

$$\begin{aligned} R_{i,f}^{\mathrm{RE}} &= B_0 \log_2(1 + \gamma_{i,f}^{\mathrm{RE}}) \\ &= B_0 \log_2 \left(1 + \frac{G_{i,U}^{\mathrm{G2A}} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,U}^{\mathrm{G2A}} P_{j,B,f}^{\mathrm{G2G}}} \right). \end{aligned} \tag{11}$$

After the UAV receives the UL data from the i-th UL GU, the UAV relays the data to the BS. The BS is assumed to successfully use SIC^2 to decode the different data from the direct and the relay links. Because the links from the UAV to the BS are the A2G channel with LoS, their channel gains are much stronger than those of the direct links. Based on the principle of the PD-NOMA scheme, the strongest signal should be decoded first. Correspondingly, in our system, when the BS receives the superimposed signals, the data from the UAV can be firstly decoded by the BS, verifying the effectiveness of NOMA in the UAV aided system model. Hence, the received signal $y_{\mathrm{BS}}^{\mathrm{UL}}$ of the BS is composed of the FD introduced DL self-interference, the enhanced messages from the UAV and the i-th UL GU, the G2G message from the j-th UL GU and the noise. It can be expressed as

$$\begin{aligned} y_{\mathrm{BS}}^{\mathrm{UL}} = & \sqrt{G_{j,B,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}}} x_{GU_j}^{\mathrm{UL}} + \sqrt{G_{U,B}^{\mathrm{RE}} P_{i,f}^{\mathrm{RE}}} x_{\mathrm{UAV}}^{\mathrm{UL}} \\ & + \sqrt{G_{i,B,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2G}}} x_{GU_i}^{\mathrm{UL}} + z_0 + I_s(x_{\mathrm{BS}}^{DL_i} + x_{\mathrm{BS}}^{DL_j}). \end{aligned} \tag{12}$$

where $x_{GU_j}^{\mathrm{UL}}$ is the G2G message from the j-th UL GU, $x_{\mathrm{UAV}}^{\mathrm{UL}}$ is the message from the UAV, $x_{GU_i}^{\mathrm{UL}}$ is the messages from the i-th UL GU, $x_{BS}^{DL_i}$ and $x_{BS}^{DL_j}$ are the FD introduced DL self-interference for the i-th DL GU and j-th DL GU.

According to the analysis of the received signals for the i-th DL GU, the j-th DL GU and the UAV, the RSS of the enhanced messages from the UAV and the i-th UL GU is much stronger than that from the j-th UL GU. Similar to the UAV, we assume that the FD introduced DL self-interference is canceled, using the SIC^2 of NOMA, the enhanced messages of the i-th GU and the signals of the j-th GU can be decoded one by one. The UL SINR of the i-th GU on subchannel f can be expressed as

$$\gamma_{i,U,f}^{\mathrm{UL}} = \frac{G_{U,B}^{\mathrm{RE}} P_{i,f}^{\mathrm{RE}} + G_{i,B,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,B,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}}} \tag{13}$$

The UL SINR of the j-th GU on subchannel f can be expressed as

$$\gamma_{j,B,f}^{\mathrm{UL}} = \frac{G_{j,B,f}^{G2G} P_{j,B,f}^{\mathrm{G2G}}}{N_0 B_0}. \tag{14}$$

Based on the Shannon's capacity theorem, the UL capacity from the i-th UL GU to the UAV on subchannel f can be calculated as:

$$\begin{aligned} R_{i,U,f}^{\mathrm{G2A}} &= B_0 \log_2(1 + \gamma_{i,U,f}^{\mathrm{UL}}) \\ &= B_0 \log_2\left(1 + \frac{G_{U,B}^{\mathrm{RE}} P_{i,f}^{\mathrm{RE}} + G_{i,B,f}^{G2G} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,B,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}}}\right). \end{aligned} \tag{15}$$

After the BS decodes the signals for the i-th UL GU, the UL capacity from the j-th UL GU to the BS can be computed as:

$$\begin{aligned} R_{j,B,f}^{\mathrm{G2G}} &= B_0 \log_2(1 + \gamma_{j,B,f}^{\mathrm{UL}}) \\ &= B_0 \log_2\left(1 + \frac{G_{j,B,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}}}{N_0 B_0}\right). \end{aligned} \tag{16}$$

IV. Problem Formulation

According to the above models and assumptions, we formulate a joint UL/DL resource allocation-based optimization problem for N GUs randomly distributed in the coverage area of the cell. The UAV and the GUs are assumed energy limited. Therefore, the consumed power should be considered in the optimization. The total consumed power consists of the UL/DL transmission power as follows:

$$P = P^{\mathrm{UL}} + P^{\mathrm{DL}}. \tag{17}$$

where P^{UL} and P^{DL} denotes the UL and DL transmission power, respectively.

The UL consumed power consists of the transmission power of the UL GUs. Thus, P^{UL} can be expressed as $P^{\mathrm{UL}} = \sum_{i=1}^{N} P_i$, where P_i is the consumed power of the i-th UL GU, which is expressed as $P_i = \sum_{f=1}^{F_T} P_{i,f}$, where $P_{i,f}$ denotes the UL transmission power of the i-th GU on subchannel f. Thus, it can be expressed as $P_{i,f} = \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} + y_{i,f}^{\mathrm{B}} P_{i,B,f}^{\mathrm{G2G}} \right)$, where $x_{i,f}^{\mathrm{U}}$ and $y_{i,f}^{B}$ are binary variables that are determined by the results of the receiver and subchannel assignment for the i-th GU. The same setting as in [25], if the UAV is assigned to relay the UL of the i-th GU on subchannel f, $x_{i,f}^{\mathrm{U}} = 1$, otherwise, $x_{i,f}^{\mathrm{U}} = 0$. Oppositely, if the i-th UL GU is directly linked to the BS on subchannel f, $y_{i,f}^{\mathrm{B}} = 1$, otherwise $y_{i,f}^{\mathrm{B}} = 0$. In addition, we prefer to accommodate different GUs on the same subchannels for the diversity gains of the G2G and the G2A links [25]. Hence, a practical constrain can be as $x_{i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} \leq 1$.

Accordingly, the consumed power of the GUs in the UL is defined as

$$P^{\mathrm{UL}} = \sum_{i=1}^{N} \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} + y_{i,f}^{\mathrm{B}} P_{i,B,f}^{\mathrm{G2G}} \right). \tag{18}$$

Moreover, the DL consumed transmission power is considered the sum of the power consumed by the BS. It is assumed that the DL subchannel is the same as the UL subchannel for each GU. Accordingly, the DL power P^{DL} is expressed as:

$$P^{\mathrm{DL}} = \sum_{i=1}^{N} \sum_{f=1}^{F_T} (x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} P_{B,i,f}^{\mathrm{B}}). \tag{19}$$

Accordingly, the sum of the consumed power in the UL and DL in (17) can be further expressed as:

$$P = \sum_{i=1}^{N} \left\{ \sum_{f=1}^{F_T} \left[\begin{array}{c} \left(x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} + y_{i,f}^{\mathrm{B}} P_{i,B,f}^{\mathrm{G2G}} \right) \\ + \left(x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} P_{B,i,f}^{\mathrm{B}} \right) \end{array} \right] \right\}. \tag{20}$$

Following the optimization target, QoS demands for the GUs should be considered [25]. P_i^{UL} and P_i^{DL} denote the total UL/DL transmission power of the i-th GU, respectively. R_i^{UL} and R_i^{DL} denote the total sum rate of the i-th GU in UL/DL, respectively. γ_i^{UL} and γ_i^{DL} denote the SINR of the i-th GU on subchannel f in the UL/DL respectively. Similarly, $P_i^{\mathrm{UL}*}$ and $P_i^{\mathrm{DL}*}$ are the i-th UL and DL GU's maximum power budget, $R_i^{\mathrm{UL}*}$, $R_i^{\mathrm{DL}*}$, $\gamma_i^{\mathrm{UL}*}$ and $\gamma_i^{\mathrm{DL}*}$ are the minimum QoS demands.

Then, QoS constraints for the i-th GUs are given by

$$\begin{cases} P_i^{\mathrm{UL}} \le P_i^{\mathrm{UL}*}, P_i^{\mathrm{DL}} \le P_i^{\mathrm{DL}*} \\ R_i^{\mathrm{UL}} \ge R_i^{\mathrm{UL}*}, R_i^{\mathrm{DL}} \ge R_i^{\mathrm{DL}*} \\ \gamma_i^{\mathrm{UL}} \ge \gamma_i^{\mathrm{UL}*}, \gamma_i^{\mathrm{DL}} \ge \gamma_i^{\mathrm{DL}*}. \end{cases} \tag{21}$$

Besides the QoS constrains for the GUs, the demands of the capacity and the power consumption for the UAV in the UL must be considered as well as the BS in DL. If P_{UAV}^* and P_{BS}^* denote the power budget of the UAV in the UL and the BS in DL, respectively, it must be guaranteed that $P_{\mathrm{UAV}} \le P_{\mathrm{UAV}}^*$ and $P_{\mathrm{BS}} \le P_{\mathrm{BS}}^*$. Finally, the joint UL/DL resource allocation problem of the UAV and the GUs based on the UAV-aided FD-NOMA method can be formulated as:

$$\begin{aligned} &(P1): \min\ P,\ \text{subject to}: \\ &(C1)\ \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} + y_{i,f}^{\mathrm{B}} P_{i,B,f}^{\mathrm{G2G}}\right) \le P_i^{\mathrm{UL}*} \\ &(C2)\ \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} P_{B,i,f}^{\mathrm{B}}\right) \le P_i^{\mathrm{DL}*} \\ &(C3)\ \sum_{i=1}^{N}\sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{i,f}^{\mathrm{RE}} \le P_{\mathrm{UAV}}^* \\ &(C4)\ \sum_{i=1}^{N}\sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} P_{B,i,f}^{\mathrm{B}}\right) \le P_{\mathrm{BS}}^* \\ &(C5)\ P_{i,U,f}^{\mathrm{G2A}}, P_{i,B,f}^{\mathrm{G2G}}, P_{i,f}^{\mathrm{RE}}, P_{B,i,f}^{\mathrm{U}}, P_{B,i,f}^{\mathrm{B}} > 0 \\ &(C6)\ \sum_{f=1}^{F_T} \left[x_{i,f}^{\mathrm{U}} \min(R_{i,U,f}^{\mathrm{G2A}}, R_{i,f}^{\mathrm{RE}}) + y_{i,f}^{\mathrm{B}} R_{i,B,f}^{\mathrm{G2G}}\right] \ge R_i^{\mathrm{UL}*} \\ &(C7)\ \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} R_{B,i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} R_{B,i,f}^{\mathrm{B}}\right) \ge R_i^{\mathrm{DL}*} \ge R_i^{\mathrm{UL}*} \\ &(C8)\ \gamma_{i,U,f}^{\mathrm{UL}} \ge \gamma_i^{\mathrm{UL}*}, \gamma_{i,B,f}^{\mathrm{UL}} \ge \gamma_i^{\mathrm{UL}*}, \gamma_{B,i,f}^{\mathrm{G2G}} \ge \gamma_i^{\mathrm{DL}*}, \gamma_{i,f}^{\mathrm{RE}} \ge \gamma_i^{\mathrm{UL}*} \\ &(C9)\ x_{i,f}^{\mathrm{U}} + y_{i,f}^{\mathrm{B}} \le 1 \\ &(C10)\ \sum_{i=1}^{N} x_{i,f}^{\mathrm{U}} \le 1, \sum_{i=1}^{N} y_{i,f}^{\mathrm{B}} \le 1 \\ &(C11)\ x_{i,f}^{\mathrm{U}}, y_{i,f}^{\mathrm{B}} \in \{0,1\} \end{aligned} \tag{22}$$

The constraints (C1) and (C2) imply that the transmission power constraint of the i-th GU in the UL/DL, respectively, cannot exceed certain budgets. Additionally, constraint (C3) and (C4) state that the total transmission power constraint of the UAV and the BS cannot exceed a certain budget. Constraints (C5) and (C6) represent the power and the rate constraints for UL/DL GUs and the UAV, respectively.

Aside from the power constraints, constraints (C7) and (C8) represent the QoS constraint for the GUs in the UL/DL. Furthermore, constraints (C9)-(C11) are the subchannel assignment rules for the i-th GU. Furthermore, if the i-th and j-th GU are assumed to share the subchannel f, then the SINR expression of the i-th GU and the UAV in constraint (C8) can be denoted in detail as:

$$\gamma_{i,f}^{\mathrm{UL}} = \begin{cases} \gamma_{i,U,f}^{\mathrm{G2A}}, \text{if } x_{i,f}^{\mathrm{U}} = y_{j,f}^{\mathrm{B}} = 1 \\ \gamma_{i,B,f}^{\mathrm{G2G}}, \text{if } y_{i,f}^{\mathrm{B}} = x_{j,f}^{\mathrm{U}} = 1 \end{cases} = \begin{cases} \dfrac{G_{U,B}^{\mathrm{RE}} P_{i,f}^{\mathrm{RE}} + G_{i,B,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,B,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}}}, \\ \text{if } x_{i,f}^{\mathrm{U}} = y_{j,f}^{\mathrm{B}} = 1 \\ \dfrac{G_{i,B,f}^{\mathrm{G2G}} P_{i,B,f}^{\mathrm{G2G}}}{N_0 B_0},\ \text{if } y_{i,f}^{\mathrm{B}} = x_{j,f}^{\mathrm{U}} = 1 \end{cases} \tag{23}$$

$$\gamma_{i,f}^{\mathrm{DL}} = \begin{cases} \dfrac{G_{B,i,f}^{\mathrm{G2G}} P_{B,i,f}^{\mathrm{U}}}{N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} P_{B,j,f}^{\mathrm{B}}}, \\ \text{if } x_{i,f}^{\mathrm{U}} = y_{j,f}^{\mathrm{B}} = 1 \\ \dfrac{G_{B,i,f}^{\mathrm{G2G}} P_{B,i,f}^{\mathrm{B}}}{N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}}, \text{if } y_{i,f}^{\mathrm{B}} = x_{j,f}^{\mathrm{U}} = 1 \end{cases} \tag{24}$$

$$\gamma_{i,f}^{\mathrm{RE}} = \begin{cases} \dfrac{G_{i,U}^{\mathrm{G2A}} P_{i,U,f}^{\mathrm{G2A}}}{N_0 B_0 + G_{j,U}^{\mathrm{G2A}} P_{j,B,f}^{\mathrm{G2G}}}, \text{if } x_{i,f}^{\mathrm{U}} = y_{j,f}^{\mathrm{B}} = 1 \\ 0, \text{if } y_{i,f}^{\mathrm{B}} = x_{j,f}^{\mathrm{U}} = 1 \end{cases} \tag{25}$$

where $i \ne j$ is considered in above Eqs. (23)–(25).

V. Our Proposed Stepwise Method based on MP

The joint resource allocation problem (P1) indicates that the variables that have to be optimized include binary variables (i.e., $x_{i,f}^{\mathrm{U}}$ and $y_{i,f}^{\mathrm{B}}$) and nonnegative continuous variables (i.e., $P_{i,U,f}^{\mathrm{G2A}}$, $P_{i,B,f}^{\mathrm{G2G}}$, $P_{i,f}^{\mathrm{RE}}$, $P_{B,i,f}^{\mathrm{U}}$, and $P_{B,i,f}^{\mathrm{B}}$). According to the theory of convex optimization, it is evident that the original problem is a non-convex mixed-integer nonlinear programming (MINLP), which is NP-hard to solve. To solve this problem, we propose a resource allocation scheme that decouples the original problem into five sub-problems, namely, receiver determination, power allocation, user pairing, subchannel assignment, and access control.

A. Step 1: Receiver Determination

According to [25], the priorities for the receiver determination of the i-th GU can be calculated in terms of the locations of the GUs and the excessive path loss as

$$AP_i^{\mathrm{U/B}} = \eta_i^{C_{AP}} d_{i,B}^{(\alpha_G - \alpha_A)} \tag{26}$$

where η_i denotes the excessive path loss coefficient of each GU, $d_{i,B}$ denotes the distance between the i-th GU and the BS,α_G denotes the path loss factor of the G2G channel, α_A denotes the path loss factor of the A2G channel, and C_{AP} is a preset constant. According to [24, 25], if $AP_i^{\mathrm{U/B}}$ is large, the i-th GU is more likely to be assigned to the UAV in the UL; otherwise, the i-th GU will more likely transmit signals to the BS directly in the UL. Moreover, the minimum number of subchannels required by the i-th GU are denoted as F_i. These are the same in the UL/DL and can be calculated on the basis of the QoS targets as [25]:

$$F_i = \left\lfloor \frac{R_i^{\mathrm{UL}*}}{B_0 \log_2(1 + \gamma_i^{\mathrm{UL}*})} \right\rfloor. \tag{27}$$

B. Step 2: Initial Power Allocation

We use an example in which the result of the receiver determination shows that in the UL, the i-th GU is relayed by the UAV and the j-th GU directly communicates with the BS; both are paired on subchannel f. Additionally, the UL SINR constraints for the UAV are assumed to be the same as those for the GUs. According to the constraint (C8) and (10), (13) and (14), the UL transmission power constraints can be represented as follows:

$$P_{j,B,f}^{\mathrm{G2G}} \geq \frac{\gamma_j^{\mathrm{UL}*} N_0 B_0}{G_{j,B,f}^{\mathrm{G2G}}} \tag{28}$$

$$P_{i,U,f}^{\mathrm{G2A}} \geq \frac{\gamma_{i,f}^{\mathrm{RE}} N_0 B_0 (G_{j,B,f}^{\mathrm{G2G}} + G_{j,U}^{\mathrm{G2A}} \gamma_j^{\mathrm{UL}*})}{G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}}} \tag{29}$$

$$P_{i,f}^{\mathrm{RE}} \geq \frac{N_0 B_0}{G_{j,B,f}^{\mathrm{G2G}} G_{i,U}^{G2A} G_{U,B}^{\mathrm{RE}}} \left[\begin{array}{l} \gamma_i^{\mathrm{UL}} G_{j,B,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} \left(1 + \gamma_j^{\mathrm{UL}*}\right) \\ -G_{i,B,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,B,f}^{\mathrm{G2G}} \\ -G_{i,B,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} \gamma_j^{\mathrm{UL}*} G_{j,U}^{\mathrm{G2A}} \end{array} \right] \tag{30}$$

Similarly, according to the constraints (C5)–(C8) and (4) and (7), the DL power constraints for the BS on the subchannel f can be rewritten as follows:

$$P_{B,i,f}^{\mathrm{U}} + P_{B,j,f}^{\mathrm{B}} \leq P_B^* \tag{31}$$

$$P_{B,j,f}^{\mathrm{B}} \geq \frac{\gamma_j^{\mathrm{DL}*} N_0 B_0}{G_{B,j,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}}} \left(\begin{array}{l} G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}} \\ +g_{i,j,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,B,f}^{\mathrm{G2G}} \\ +g_{i,j,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,U}^{\mathrm{G2A}} \gamma_j^{\mathrm{UL}*} \end{array} \right). \tag{32}$$

$$P_{B,i,f}^{\mathrm{U}} \geq \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0}{G} \left(\begin{array}{l} G_{i,U}^{\mathrm{G2A}} G_{B,j,f}^{G2G} G_{j,B,f}^{\mathrm{G2G}} \\ +\gamma_j^{\mathrm{UL}*} G_{i,U}^{\mathrm{G2A}} G_{B,j,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \\ +\gamma_j^{\mathrm{DL}*} G_{B,i,f}^{\mathrm{G2G}} G_{j,B,f}^{G2G} G_{i,U}^{\mathrm{G2A}} \\ +\gamma_{i,f}^{\mathrm{RE}} \gamma_j^{\mathrm{DL}*} G_{B,i,f}^{\mathrm{G2G}} G_{j,B,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \\ +\gamma_j^{\mathrm{DL}*} \gamma_j^{\mathrm{UL}*} \gamma_{i,f}^{\mathrm{RE}} G_{j,U}^{\mathrm{G2A}} G_{B,i,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \end{array} \right) \tag{33}$$

$$G = G_{i,U}^{\mathrm{G2A}} G_{B,j,f}^{\mathrm{G2G}} G_{j,B,f}^{\mathrm{G2G}} G_{B,i,f}^{\mathrm{G2G}} \tag{34}$$

Each power item in (20) should be minimized to reduce the power sum of the devices. Based on the minimum SINR requirements, the transmission power of the GUs, the UAV, and the BS on each subchannel can be initialized as follows:

$$P_{j,B,f}^{\mathrm{G2G}} = \frac{\gamma_j^{\mathrm{UL}*} N_0 B_0}{G_{j,B,f}^{\mathrm{G2G}}} \tag{35}$$

$$P_{i,U,f}^{\mathrm{G2A}} = \frac{\gamma_{i,f}^{\mathrm{RE}} N_0 B_0 (G_{j,B,f}^{\mathrm{G2G}} + G_{j,U}^{\mathrm{G2A}} \gamma_j^{\mathrm{UL}*})}{G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}}} \tag{36}$$

$$P_{i,f}^{\mathrm{RE}} = \frac{N_0 B_0}{G_{j,B,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} G_{U,B}^{\mathrm{RE}}} \left[\begin{array}{l} \gamma_i^{\mathrm{UL}} G_{j,B,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} \left(1 + \gamma_j^{\mathrm{UL}*}\right) \\ -G_{i,B,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,B,f}^{\mathrm{G2G}} \\ -G_{i,B,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} \gamma_j^{\mathrm{UL}*} G_{j,U}^{\mathrm{G2A}} \end{array} \right] \tag{37}$$

$$P_{B,i,f}^{\mathrm{U}} = \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0}{G} \left(\begin{array}{l} G_{i,U}^{\mathrm{G2A}} G_{B,j,f}^{\mathrm{G2G}} G_{j,B,f}^{\mathrm{G2G}} \\ +\gamma_j^{\mathrm{UL}*} G_{i,U}^{\mathrm{G2A}} G_{B,j,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \\ +\gamma_j^{DL*} G_{B,i,f}^{G2G} G_{j,B,f}^{\mathrm{G2G}} G_{i,U}^{G2A} \\ +\gamma_{i,f}^{RE} \gamma_j^{\mathrm{DL}*} G_{B,i,f}^{\mathrm{G2G}} G_{j,B,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \\ +\gamma_j^{\mathrm{DL}*} \gamma_j^{\mathrm{UL}*} \gamma_{i,f}^{\mathrm{RE}} G_{j,U}^{\mathrm{G2A}} G_{B,i,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \end{array} \right) \tag{38}$$

$$P_{B,j,f}^{\mathrm{B}} = \frac{\gamma_j^{\mathrm{DL}*} N_0 B_0}{G_{B,j,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}}} \left(\begin{array}{l} G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}} \\ +g_{i,j,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,B,f}^{\mathrm{G2G}} \\ +g_{i,j,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,U}^{\mathrm{G2A}} \gamma_j^{\mathrm{UL}*} \end{array} \right) \tag{39}$$

According to the above access-priority (26), it is assumed that the i-th GU is connected to the UAV, and the j-th GU is connected to the BS. Meanwhile, in the DL, the G2G channel of the j-th GU must be better than that of the i-th GU. On the other hand, for the i-th GU, the G2A channel status with the UAV must be better than the G2G channel status with the BS.

C. Step 3: User Pairing

According to the UL receiver priority in (26), the GUs are divided into two groups, as shown in Fig. 2. The communication of the first GU group is relayed by the UAV, and the other group directly communicates with the BS. It is assumed that the DL GUs are paired in the same manner as that in the UL. Thus, the GUs are paired according to the minimum sum of the transmission power of all paired GUs in the UL as:

$$\min \sum_{i=1}^{N/2} \sum_{j=1}^{N/2} U_{i,j} \bar{P}_{i,j}, \ U_{i,j} \in \{0,1\}, \tag{40}$$

where $\bar{P}_{i,j} = (1/F_T) \sum_{f=1}^{F_T} \left(P_{i,U,f}^{\mathrm{G2A}} + P_{j,B,f}^{\mathrm{G2G}} \right)$ is the power sum of the paired GUs, $U_{i,j}$ is a binary variable. If the i-th GU is paired with the j-th GU, then $U_{i,j} = 1$; otherwise, $U_{i,j} = 0$. The paired user problem can be considered an assignment problem, which can be optimally solved using the Hungarian algorithm [31]. Considering the user pairing scheme with worst-case, the time complexity of the user-paring algorithm is $O(N^3)$, where N is the number of the GUs.

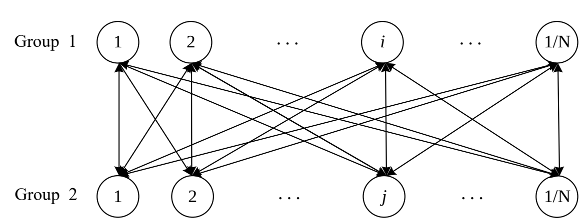

Fig. 2. User pairing.

D. Step 4: Message Passing-based Subchannel Assignment

It is assumed that the associated GUs need the same number of subchannels and the assigned channels that the DL GUs need are the same as that the UL GUs need. The i-th GU is assumed to be paired with the j-th GU, thus, $x_{i,f}^{\mathrm{U}} = y_{j,f}^{\mathrm{B}}$.

Hence, (22) can be reformulated as:

$$\min\sum_{i=1}^{N}\sum_{f=1}^{f_T} x_{i,f}^{\mathrm{U}} P_{i,f}^{\mathrm{IJW}},\ \text{subject to:}$$
$$(C1')\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} \le P_i^{\mathrm{UL}*},\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{j,B,f}^{\mathrm{G2G}} \le P_i^{\mathrm{UL}*}$$
$$(C2')\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}} \le P_i^{\mathrm{DL}*},\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{B,j,f}^{\mathrm{B}} \le P_j^{\mathrm{DL}*}$$
$$(C3')\ \sum_{i=1}^{N}\sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{i,f}^{\mathrm{RE}} \le P_{\mathrm{UAV}}^{*}$$
$$(C4')\ \sum_{i=1}^{N}\sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} \left(P_{B,i,f}^{\mathrm{U}} + P_{B,j,f}^{\mathrm{B}}\right) \le P_{\mathrm{BS}}^{*}$$
$$(C5')\ P_{i,U,f}^{\mathrm{G2A}}, P_{j,B,f}^{\mathrm{G2G}}, P_{i,f}^{\mathrm{RE}}, P_{B,i,f}^{\mathrm{U}}, P_{B,j,f}^{\mathrm{B}} > 0$$
$$(C6')\ \sum_{f=1}^{F_T} \left[x_{i,f}^{\mathrm{U}} \min\left(R_{i,U,f}^{\mathrm{G2A}}, R_{i,f}^{\mathrm{RE}}\right)\right] \ge R_i^{\mathrm{UL}*},$$
$$\sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} R_{j,B,f}^{\mathrm{G2G}} \ge R_j^{\mathrm{UL}*}$$
$$(C7')\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} R_{B,i,f}^{\mathrm{U}} \ge R_i^{\mathrm{DL}*} \ge R_i^{\mathrm{UL}*},$$
$$\sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} R_{B,j,f}^{\mathrm{B}} \ge R_j^{\mathrm{DL}*} \ge R_j^{\mathrm{UL}*}$$
$$(C8')\ \gamma_{i,U,f}^{\mathrm{UL}} \ge \gamma_i^{\mathrm{UL}*}, \gamma_{j,B,f}^{\mathrm{UL}} \ge \gamma_j^{\mathrm{UL}*}, \gamma_{B,i,f}^{\mathrm{G2G}} \ge \gamma_i^{\mathrm{DL}*},$$
$$\gamma_{B,j,f}^{\mathrm{G2G}} \ge \gamma_j^{\mathrm{DL}*}, \gamma_{i,f}^{\mathrm{RE}} \ge \gamma_i^{\mathrm{UL}*}$$
$$(C9')\ \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} = F_i$$
$$(C10')\ \sum_{i=1}^{N} x_{i,f}^{\mathrm{U}} \le 1$$
$$(C11')\ x_{i,f}^{\mathrm{U}} \in \{0,1\} \tag{41}$$

where $P_{i,f}^{\mathrm{IJW}} = P_{i,U,f}^{\mathrm{G2A}} + P_{j,B,f}^{\mathrm{G2G}} + P_{B,i,f}^{\mathrm{U}} + P_{B,j,f}^{\mathrm{B}}$ is the power sum of the paired GUs on the subchannel f in the UL/DL. F_i is the number of requested subchannels of the i-th GU, calculated according to (27). According to [25, 32], the subchannel assignment problem can be solved by the message-passing (MP) algorithm [33] with iterative computations as:

$$\psi_{i,f}^{(t+1)} = P_{i,f}^{\mathrm{IJW}} - \rho_i \left\{\psi_{z,i}^{(t)} + P_{i,z}^{\mathrm{IJW}}\right\}_{F_i^{th}} - (1-\rho_i)\left(P_{i,f}^{\mathrm{IJW}} + \psi_{f,i}^{(t)}\right),\ z \neq f \tag{42}$$

$$\psi_{f,i}^{(t+1)} = -\rho_i \min_{l \neq i} \psi_{l,f}^{(t+1)} - (1-\rho_i)\,\psi_{i,f}^{(t+1)} \tag{43}$$

$$\xi_{i,f}^{(t)} = \psi_{f,i}^{(t)} + \psi_{i,f}^{(t)} \tag{44}$$

$$x_{i,f}^{\mathrm{U}} = \begin{cases} 1, & \text{if } \xi_{i,f}^{(t)} < 0 \\ 0, & \text{otherwise} \end{cases}, \tag{45}$$

$$x_{i,f}^{U(T^*)} = x_{i,f}^{U(T^*-1)}, \forall i, f. \tag{46}$$

The metric $x_{i,f}^{U}$ can be computed recursively, until equation (46) can be satisfied at time T^* to obtain an optimal result of the subchannel assignment scheme for the UAV uplinked GUs. Furthermore, $\{\psi_{z,i}^{(t)} + P_{i,z}^{\mathrm{IJW}}\}_{F_i^{th}}$ denotes the $F_i{}^{th}$ sorted $\psi_{z,i}^{(t)} + P_{i,z}^{\mathrm{IJW}}$ listed in ascending order with $z \neq f$. Thus, the complexity of the subchannel assignment algorithm mainly depends on the complexity of sorting the F_i^{th} element. The pseudocode of the message passing (MP)-based subchannel assignment scheme is given in **Algorithm 1**.

Algorithm 1 The proposed MP-based subchannel assignment method for the UAV-uplinked GUs.

Input: the initialized power sum of the associated GUs $\left\{P_{i,f}^{\mathrm{IJW}}\right\}$;

1: **Initialization:** Set $\psi_{i,f}^{0} = 0$, $\psi_{f,i}^{0} = 0$;
2: **While:** $x_{i,f}^{\mathrm{U(t)}} \neq x_{i,f}^{\mathrm{U(t+1)}}, \forall i, j$, **do:**
3: Each UAV-uplinked GU sends message $\psi_{i,f}^{(t+1)}$ as in (43) to the UAV;
4: The UAV sends message $\psi_{f,i}^{(t+1)}$ as in (44) to each UAV-uplinked GU;
5: Each UAV-uplink GU computes marginal $\xi_{i,f}^{(t+1)}$ and factor $x_{i,f}^{\mathrm{U(t+1)}}$ as defined in (45) and (46) for each subchannel;
6: **End while**

Output: Result of the subchannel assignment scheme for the i-th GU: $x_{i,f}^{\mathrm{U}}, \forall i, f$.

E. Step 5: Power Limits-based Access Control

The results of the above four steps allow us to classify the GUs into UAV-uplinked users and BS-uplinked users on the subchannels. The total power of the GUs in the UL/DL and the power of the UAV can be given as:

$$P_i^{\mathrm{UL}} = \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{i,U,f}^{\mathrm{G2A}} \tag{47}$$

$$P_j^{\mathrm{UL}} = \sum_{f=1}^{F_T} y_{j,f}^{\mathrm{B}} P_{j,B,f}^{\mathrm{G2G}} \tag{48}$$

$$P_{\mathrm{UAV}} = \sum_{i \in \mathrm{RD^U}} \sum_{f=1}^{F_T} x_{i,f}^{\mathrm{U}} P_{i,f}^{\mathrm{RE}} \tag{49}$$

$$P_i^{\mathrm{DL}} = \sum_{f=1}^{F_T} \left(x_{i,f}^{\mathrm{U}} P_{B,i,f}^{\mathrm{U}}\right) \tag{50}$$

$$P_j^{\mathrm{DL}} = \sum_{f=1}^{F_T} \left(y_{j,f}^{\mathrm{B}} P_{B,j,f}^{\mathrm{B}}\right) \tag{51}$$

where P_i^{UL} is the UL power of the i-th GU relayed by the UAV, P_j^{UL} is the UL power of the j-th GU directly uplinked with the BS, P_i^{DL} and P_j^{DL} is the DL power of the i-th and the j-th GU, respectively; P_{UAV} represents the consumed power of the UAV. The power of the GUs, the UAV and the BS on each subchannel can be calculated using (35)–(39). RD^{U} in (49) denotes a GU set uplinked with the UAV according to the receiver determination results. According to the power consumption results of (47)–(51), the initial power allocation should be confirmed using the power budget constraints, i.e., (C1)–(C4).

Based on the demands of the UL/DL services for the GUs, according to [25], we adopt a soft access control scheme for the GUs and a turbo access control scheme for the UAV.

1) Soft access control scheme for the BS-uplinked GUs: If the UL service is acceptable to the j-th GU with a sum rate lower than its demand rate $R_j^{\mathrm{UL}*}$, the access control scheme can reduce the total transmission power of the j-th GU one by one. For example, if $P_j^{\mathrm{UL}} > P_j^{\mathrm{UL}*}$, the access control scheme will reduce the highest power of the j-th GU on subchannel f first. Then, the total power of the j-th GU will be recomputed. The latest power allocation is regarded as the final power allocation result until $P_j^{\mathrm{UL}} \leq P_j^{\mathrm{UL}*}$ is satisfied. Otherwise, the soft access control scheme is performed uninterruptedly until it satisfies the power budget constraint.

2) Soft access control scheme for the UAV-uplinked GUs: According to the access control results for the BS-uplinked GUs, the power of the UAV-uplinked GUs can also be confirmed. If the power of the j-th UL GU on subchannel f is assumed to decrease, the power of the paired i-th GU on subchannel f in the UL can be updated as follows:

$$P_{i,U,f}^{\prime\mathrm{G2A}} = \frac{N_0 B_0 \gamma_i^{\mathrm{UL}*}}{G_{i,U}^{\mathrm{G2A}}} \tag{52}$$

After obtaining the total updated UL power consumption of the i-th UL GU by (47) and (48), the total uplink power of the i-th GU can also be confirmed by the soft access control. If $P_i^{\mathrm{UL}} > P_i^{\mathrm{UL}*}$, the power of the i-th GU on the assigned subchannels is reduced one by one in descending order until $P_i^{\mathrm{UL}} \leq P_i^{\mathrm{UL}*}$ is satisfied.

3) Turbo access control scheme for the UAV: We observed in (37) that the power of the UAV is influenced by the UL/DL. The power updated for the DL GUs and the UAV should be considered simultaneously. According to the access control results of the UL GUs, the transmission power of the UAV on each subchannel is updated in the following three cases.

Case 1: If the initialized power of the i-th GU and the j-th GU on subchannel f in the UL/DL are not reduced, the power of the UAV, the i-th DL GU, and the j-th DL GU remain the same as in (37)–(39).

Case 2: If the initialized power of the i-th GU uplinked to the UAV on subchannel f is reduced in the UL, $P_{i,f}^{\mathrm{RE}}$ is updated as zero, regardless of how the power of the j-th GU uplinked to the BS changes. In contrast, regardless of how the initialized power of the j-th UL GU is reduced,according to (24), the power of the j-th DL GU is updated as follows:

$$\begin{aligned} P_{B,j,f}^{\prime\mathrm{B}} &= \frac{\gamma_j^{DL*}\left(N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\mathrm{G2A}}\right)}{G_{B,j,f}^{\mathrm{G2G}}} \\ &= \frac{\gamma_j^{\mathrm{DL}*} N_0 B_0}{G_{B,j,f}^{\mathrm{G2G}}} \end{aligned} \tag{53}$$

For the power of the i-th DL GU, two cases need to be considered. In the first case, if the initialized power of the j-th UL GU is not reduced, $P_{B,i,f}^{\mathrm{U}}$ is updated as follows:

$$\begin{aligned} P_{B,i,f}^{\prime\mathrm{U}} &= \frac{\gamma_i^{DL*}\left(N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} P_{B,j,f}^{\prime\mathrm{B}}\right)}{G_{B,i,f}^{\mathrm{G2G}}} \\ &= \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0 \left(G_{B,j,f}^{\mathrm{G2G}} + \gamma_j^{\mathrm{UL}*} g_{i,j,f}^{\mathrm{G2G}} + \gamma_j^{\mathrm{DL}*} G_{B,i,f}^{\mathrm{G2G}}\right)}{G_{B,i,f}^{\mathrm{G2G}} G_{B,j,f}^{\mathrm{G2G}}} \end{aligned} \tag{54}$$

In the second case, if the initialized power of the j-th BS uplinked GU is reduced, $P_{B,i,f}^{\mathrm{U}}$ and $P_{i,f}^{\mathrm{RE}}$ are updated as:

$$P_{B,i,f}^{\prime\prime\mathrm{U}} = \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0 \left(G_{B,j,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} \gamma_j^{\mathrm{DL}*}\right)}{G_{B,i,f}^{\mathrm{G2G}} G_{B,j,f}^{\mathrm{G2G}}} \tag{55}$$

Case 3: If only the initialized power of the j-th BS uplinked GU on subchannel f is reduced in the UL, according to (23) and (25), $P_{i,f}^{\mathrm{RE}}$ and $P_{i,U,f}^{\mathrm{G2A}}$ can be updated as:

$$P_{i,f}^{\prime\mathrm{RE}} = \frac{N_0 B_0 \gamma_i^{\mathrm{UL}*}}{G_{U,B}^{\mathrm{RE}}} \tag{56}$$

$$\begin{aligned} P_{i,U,f}^{\prime\mathrm{G2A}} &= \frac{\gamma_{i,f}^{\mathrm{RE}}\left(N_0 B_0 + G_{j,U}^{\mathrm{G2A}} P_{j,B,f}^{\mathrm{G2A}}\right)}{G_{i,U}^{\mathrm{G2A}}} \\ &= \frac{N_0 B_0 \gamma_i^{\mathrm{UL}*}}{G_{i,U}^{\mathrm{G2A}}} \end{aligned} \tag{57}$$

According to the updated transmission power of the UAV on all assigned subchannels, the total power of the UAV can be calculated using (49). Finally, the power of the UAV should be confirmed by the power budget constraint (C3). Meanwhile, according to (24), the power of the j-th DL GU $P_{B,j,f}^{\mathrm{B}}$ is updated as:

$$\begin{aligned} P_{B,j,f}^{\prime\prime\mathrm{B}} &= \frac{\gamma_j^{DL*}\left(N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{i,U,f}^{\prime\mathrm{G2A}}\right)}{G_{B,j,f}^{\mathrm{G2G}}} \\ &= \frac{\gamma_j^{\mathrm{DL}*} N_0 B_0 \left(G_{i,U}^{\mathrm{G2A}} + g_{i,j,f}^{\mathrm{G2G}} \gamma_i^{\mathrm{UL}*}\right)}{G_{B,j,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}}} \end{aligned} \tag{58}$$

The power of the i-th DL GU $P_{B,i,f}^{\mathrm{U}}$ is updated as:

$$\begin{aligned} P_{B,i,f}^{\prime\prime\prime\mathrm{U}} &= \frac{\gamma_i^{DL*}\left(N_0 B_0 + g_{i,j,f}^{\mathrm{G2G}} P_{j,B,f}^{\mathrm{G2G}} + G_{B,i,f}^{\mathrm{G2G}} P_{B,j,f}^{\prime\prime\mathrm{B}}\right)}{G_{B,i,f}^{\mathrm{G2G}}} \\ &= \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0}{G_{B,j,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} G_{B,i,f}^{\mathrm{G2G}}} \begin{pmatrix} G_{B,j,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} \\ +\gamma_j^{\mathrm{DL}*} G_{B,i,f}^{\mathrm{G2G}} G_{i,U}^{\mathrm{G2A}} \\ +\gamma_j^{\mathrm{DL}*} \gamma_i^{\mathrm{UL}*} G_{B,i,f}^{\mathrm{G2G}} g_{i,j,f}^{\mathrm{G2G}} \end{pmatrix} \end{aligned} \tag{59}$$

Because the UAV is the only relay for the UL GUs, the access control scheme based on the power budget of the UAV should jointly consider the UL/DL service for the relayed GUs. Because the access control scheme should be iterated among the UL GUs, the DL GUs, and the UAV until $P_i^{\mathrm{UL}} \leq P_i^{\mathrm{UL}*}$,$P_i^{\mathrm{DL}} \leq P_i^{\mathrm{DL}*}$, and $P_{\mathrm{UAV}} \leq P_{\mathrm{UAV}}^*$ are satisfied, the access control scheme for the UAV is called the turbo access control scheme.

Based on the updated DL power, the total consumed power of the DL GU can be obtained by (50) and (51) and can also be confirmed by the soft access control. If $P_i^{\mathrm{DL}} > P_i^{\mathrm{DL}*}$, the transmission power from the BS to the i-th GU on the assigned subchannels will be individually reduced in descending order until $P_i^{\mathrm{DL}} \leq P_i^{\mathrm{DL}*}$ is satisfied. Then, $P_{B,i,f}^{\mathrm{U}} = 0$, and the other power equations stay the same. For the j-th DL GU, if $P_j^{\mathrm{DL}} > P_j^{\mathrm{DL}*}$, the transmission power from the BS to the j-th GU on the assigned subchannels will be individually reduced in descending order until $P_j^{\mathrm{DL}} \leq P_j^{\mathrm{DL}*}$ is satisfied. Then, $P_{B,j,f}^{\mathrm{B}} = 0$, and $P_{i,f}^{\mathrm{RE}}$, $P_{j,B,f}^{\mathrm{G2G}}$,$P_{B,i,f}^{\mathrm{U}}$,$P_{i,U,f}^{\mathrm{G2A}}$ are updated as

$$P_{i,f}^{\mathrm{RE}} = \frac{N_0 B_0}{G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}} G_{U,B}^{\mathrm{RE}}} \left[\begin{array}{l} G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}} \gamma_i^{\mathrm{UL}} \left(1 + \gamma_j^{\mathrm{UL}*}\right) \\ -G_{i,B,f}^{\mathrm{G2G}} \gamma_{i,f}^{\mathrm{RE}} G_{j,B,f}^{\mathrm{G2G}} \\ -\gamma_{i,f}^{\mathrm{RE}} \gamma_j^{\mathrm{UL}*} G_{i,B,f}^{\mathrm{G2G}} G_{j,U}^{\mathrm{G2A}} \end{array} \right] \tag{60}$$

$$P_{j,B,f}^{\mathrm{G2G}} = \frac{\gamma_j^{\mathrm{UL}*} N_0 B_0}{G_{j,B,f}^{\mathrm{G2G}}} \tag{61}$$

$$P_{B,i,f}^{\mathrm{U}} = \frac{\gamma_i^{\mathrm{DL}*} N_0 B_0 \left[G_{j,B,f}^{\mathrm{G2G}} + g_{i,j,f}^{\mathrm{G2G}} \gamma_j^{\mathrm{UL}*} \right]}{G_{B,i,f}^{\mathrm{G2G}} G_{j,B,f}^{\mathrm{G2G}}} \tag{62}$$

$$P_{i,U,f}^{\mathrm{G2A}} = \gamma_{i,f}^{\mathrm{RE}} N_0 B_0 \frac{\left(G_{j,B,f}^{\mathrm{G2G}} + G_{j,U}^{\mathrm{G2A}} \gamma_j^{\mathrm{UL}*} \right)}{G_{i,U}^{\mathrm{G2A}} G_{j,B,f}^{\mathrm{G2G}}} \tag{63}$$

Finally, after the above five steps, the proposed joint UL/DL resource allocation scheme provides optimal results of the subchannel assignment and power assignment scheme. The results are listed in a set as $\left\{ x_{i,f}^{\mathrm{U}}; y_{i,f}^{\mathrm{B}}; P_{i,U,f}^{\mathrm{G2A}}; P_{j,B,f}^{\mathrm{G2G}}; P_{B,i,f}^{\mathrm{G2G}}; P_{B,j,f}^{\mathrm{G2G}}; P_{i,f}^{\mathrm{RE}} \right\}$.

It should be noted that, the transmission powers of GUs are reduced one by one according to the SINR in eqs. (23)–(25). For the power-reduced GU, it does not mean the service will not be offered to the reduced GU. Hence, we consider three cases as below.

Case 1: If the users are crowded and the channels are congested and moreover, other users demand high SINR, the power-reduced GU is not sensitive to time, in order to save system bandwidth, it can wait for a free channel for a while and then continue to use NOMA scheme to transmit signal again.

Case 2: If the power-reduced user is sensitive to time and its power is sufficient, it can communicate directly with the base station and use additional OFDMA channels. This is a traditional problem, and existing techniques can solve it.

Case 3: If the power-reduced user is sensitive to time, but the transmission power is not sufficient, it can use an additional OFDMA channel for transmission through the UAV. In the simulation, we take the **Case 1** for example.

In this paper, the problem in (22) is decomposed into five sub-problems without relaxation, which might bring sub-optimality to the original problem. In the proposed scheme, the local optimal solutions can be obtained in each step for the decouple sub-problems. Meanwhile, based on the proposed algorithm, although the final solutions cannot be guaranteed globally optimal, it greatly reduces the complexity of the algorithm. The significant performance improvements have been verified by the following simulation.

VI. Simulation Results and Analysis

In this section, we develop a simulation system to evaluate the performance of the proposed scheme. To build a system model for simulations, a ground cellular network is considered with a radius of $R = 200$ m. A UAV is hovering directly above the BS as the relay. The UAV's height is $H_{\mathrm{U}} = 300$ m. The total number of GUs is assumed to $N = 32$. Additionally, the channel parameters of the simulation model are considered as follows. The bandwidth of each subchannel is $B_0 = 0.3125$ MHz, and the number of the subchannels is assumed to $F_T = 32$. The power spectral density (PSD) of the noise is $N_0 = 5 \times 10^{-20}$ W/Hz. Moreover, the path loss parameters of the G2A and G2G channels are $\alpha_A = 2$ and $\alpha_G = 4$, respectively [25]. The additional attenuation fading are $\eta^{\mathrm{LoS}} = -1$ dB and $\eta^{\mathrm{NLoS}} = -10$ dB, respectively. According to [25, 28], in an urban environment, the parameters in (2) are set to $\beta = 0.16$ and $\psi = 9.6$. Furthermore, according to [34], we consider the Rayleigh fading model for the G2G channel. The demanded SINR of UL/DL is 10 dB and 20 dB, respectively. Moreover, the maximum transmission power limits for the UAV, the GUs, and the BS are 3 W, 1 W, and 30 W. Six simulation schemes are tested to compare the results of the proposed resource allocation scheme with that of different communication schemes in Table II.

TABLE II
SIMULATION SETTINGS OF DIFFERENT METHODS.

Scheme Notations	Detailed Descriptions
FD-NOMA-UAV	FD-NOMA scheme with a UAV above the BS
FD-NOMA-NUAV	FD-NOMA scheme with a BS and no UAV
OFDMA-UAV	OFDMA scheme with a BS and no UAV
FD-NUAV	FD scheme with a BS and no UAV
NOMA-NUAV	NOMA scheme with a BS and no UAV
NOMA-UAV	NOMA scheme with a UAV above the BS

In Fig. 3, the access ratios (ARs) and share ratios (SRs) of the GUs of the different schemes in Table II are compared. The AR represents the user access performance of the different schemes, which is the ratio of the GUs that can successfully access the subchannels. The SR, which is the ratio of the GUs that share the subchannels with other GUs in both the UL/DL, represents the spectrum sharing performance of the schemes. In Fig. 3, it is observed that both the SR and AR of the FD-NOMA-UAV scheme are significantly higher than those of the other schemes. The reason is that the G2A channels provide better performance for communication, resulting in more spectrum access and sharing opportunities for the GUs. In the OFDMA-NUAV scheme, only a quarter of the GUs can access the subchannel and no subchannles can be shared, while only 50% of the GUs can access in the FD-NUAV, NOMA-NUAV and NOMA-UAV schemes, and all GUs can access in both FD-NOMA schemes. Because G2A channels are more beneficial for transmitting signals and provide more

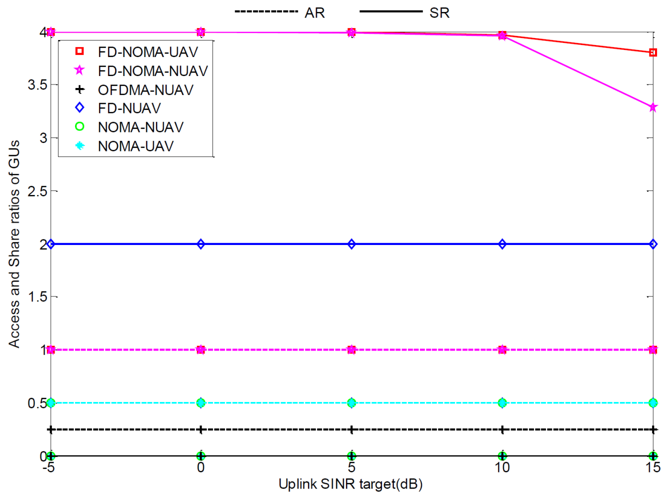

Fig. 3. The access and share ratios of the GUs versus UL SINR target.

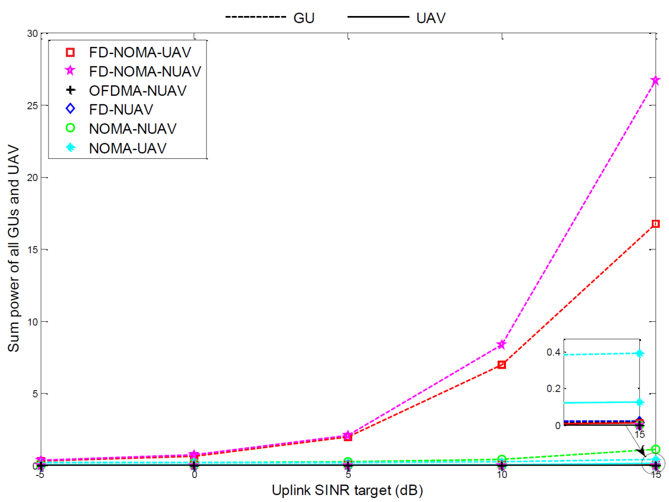

Fig. 4. The sum of UL/DL power of the GUs and the UAV versus UL SINR target.

spectrum accessing and sharing opportunities for the GUs. No subchannel can be shared in NOMA-NUAV and NOMA-UAV scheme, because users use the different shared subchannels in the UL/DL. Moreover, when the UL SINR is higher than 10 dB, the SRs of both FD-NOMA schemes decrease linearly. Because a higher SINR requires more transmission power or less interference. It is not possible to satisfy both requirements of the associated GUs. Therefore, a higher SINR will lead to more share failures in FD-NOMA schemes, causing a lower SR and AR.

In Fig. 4, the sum power of the GUs and the UAV in the UL/DL are simulated for different schemes. It is observed in Fig. 4 that the consumed power of the GUs is the most in the FD-NOMA-NUAV scheme because of the highest SR and AR. In contrast, in the FD-NOMA-UAV scheme, the GUs consume less power than that in the FD-NOMA-NUAV scheme. These results indicate that the quality of the G2A UL channel is better than that of the G2G UL channel, thereby significantly reducing the power consumption of the GUs. As shown in Fig. 4, the power consumption of the UAV is very low in two schemes with a UAV as a relay (i.e., NOMA-UAV and FD-NOMA-UAV). Meanwhile, the power consumption of the GUs in the OFDMA-NUAV scheme is very low, since only a quarter of the GUs can access the subchannels according to Fig. 3.

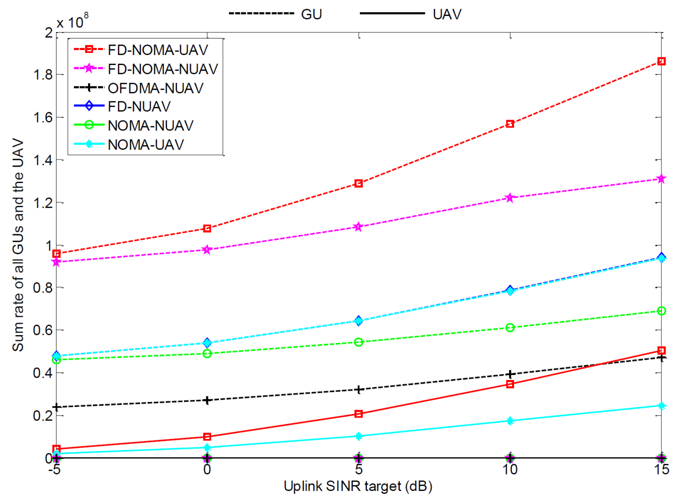

Fig. 5. The sum of UL/DL rates of the GUs and the UAV versus UL SINR target.

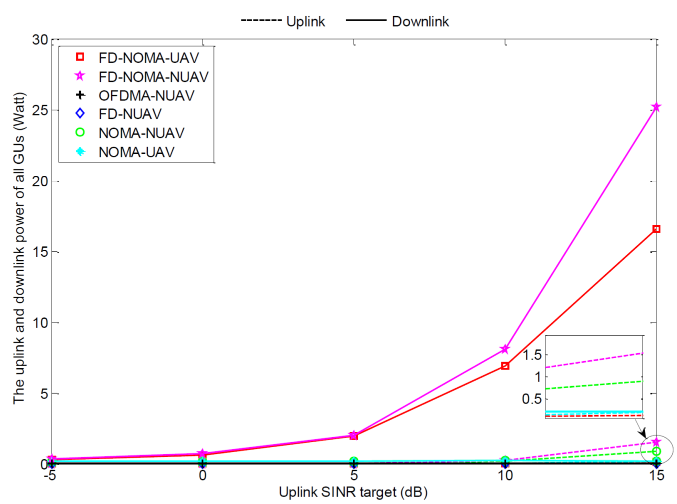

Fig. 6. UL/DL power of all GUs versus UL SINR target for the different schemes.

In Fig. 5, the sum rates of the GUs and the UAV in the UL/DL are compared for the different schemes. It is observed that the FD-NOMA-UAV resource allocation scheme has the highest rate. The FD-NOMA-UAV scheme not only consumes less power of the GUs than the FD-NOMA-NUAV scheme, but also has the highest sum rates in the UL/DL. This is because the G2A channels are more beneficial for transmitting signals. In Fig. 5, the sum rates of GUs in FD-UAV and NOMA-UAV scheme are almost the same and higher than that in the NOMA-UAV and OFDMA-UAV. The sum rates of the UAV in FD-NOMA-UAV is higher than that in NOMA-UAV scheme, since more GUs can access the subchannels thanks to the SIC[1] in FD, thereby the UAV can transmit more signals from GUs. In Fig. 6, the UL/DL power of the GUs is simulated respectively for the different schemes. In the DL, the GUs in the FD-NOMA-NUAV scheme consume the most power, and the GUs in the FD-NOMA-UAV scheme consume less DL power than those in the FD-NOMA-NUAV scheme. This result is also attributed to the G2A channel in the UL, which affects the DL power consumption. The UL power consumption of the GUs in the FD-NOMA-UAV scheme is slightly less than that in the NOMA-UAV scheme. Fig. 7 shows the UL/DL rates of the GUs simulated for the different schemes. The UL rate of the GUs in the FD-NOMA-UAV scheme is much higher than that of the other schemes. The reason should also be due to the benefit of the G2A channel. In contrast, the DL rate of the GUs is the highest in the FD-NOMA-UAV scheme. Meanwhile, when the UL SINR target is higher than 10 dB, the DL rates of the GUs in the FD-NOMA-UAV and FD-NOMA-NUAV schemes decrease because of the reduction in the SR, which is shown in Fig. 3.

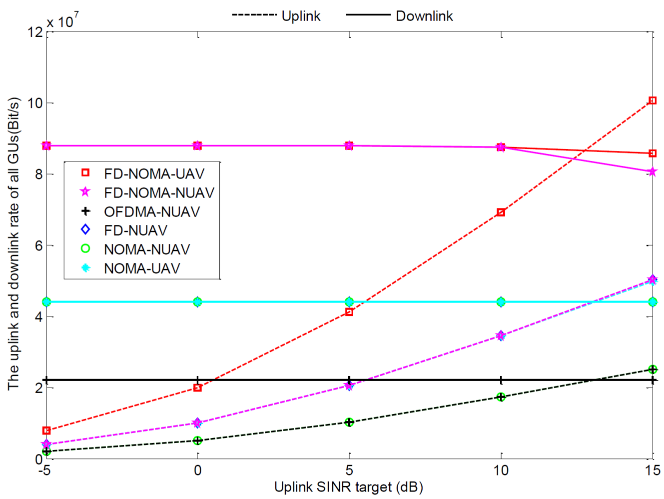

Fig. 7. UL/DL rate of all GUs versus UL SINR target.

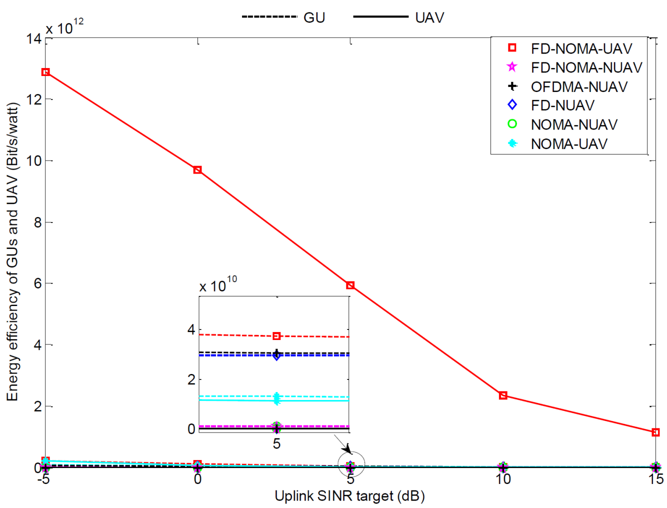

Fig. 8. The energy efficiency of the GUs and UAV versus the UL SINR target.

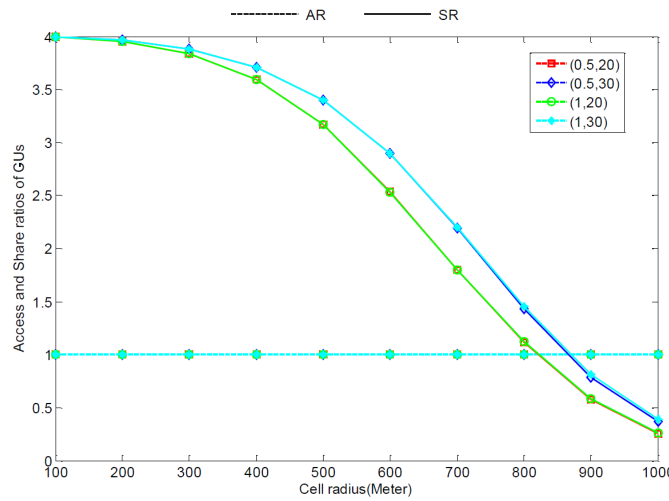

Fig. 9. The access ratio and share ratio of the GUs with the proposed resource allocation in the FD-NOMA-UAV scheme versus the cell radius for different power budgets.

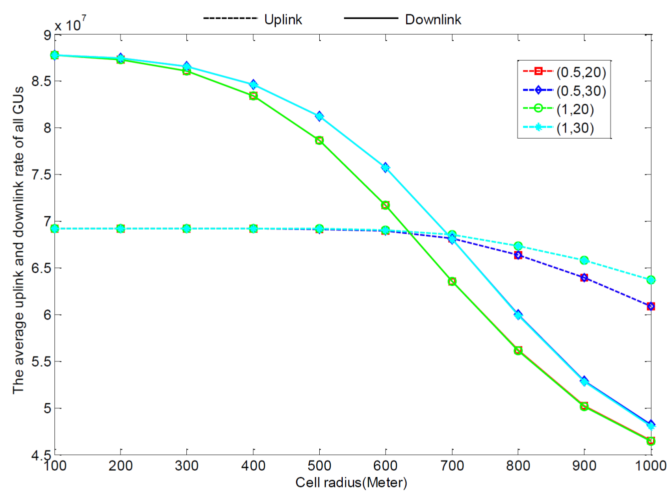

Fig. 10. UL/DL rates of the GUs with the proposed resource allocation in the FD-NOMA-UAV scheme versus the cell radius for different power budgets.

In Fig. 8, the energy efficiencies of the GUs and the UAV are simulated. It is observed that the energy efficiency of the UAV in the FD-NOMA-UAV scheme is much higher than that in the other schemes. Moreover, with the increase in the UL SINR target, the energy efficiencies of the GUs and the UAV in the FD-NOMA-UAV scheme decrease more rapidly than those in the other schemes. It is because a higher SINR requires higher power to suppress the interference. Next, the performance of the proposed resource allocation in the FD-NOMA-UAV scheme is investigated. The power budget of the GUs (P_{CU}) equals 0.5 or 1 W, and the power budget of the BS (P_{BS}) equals 20 or 30 W.

In Fig. 9, the AR and the SR of the FD-NOMA-UAV scheme for different power budgets are simulated. It can be observed that the SR decreases as the cell radius increases. Regardless of the cell radius, the ARs of the different power budgets remain the same. In Fig. 10, we observe that the UL/DL rates decrease with an increase in the cell radius, and the rate of decrease increases when the radius exceeds 200 m. The reason is that the SR decreases as the cell radius increases. Moreover, a higher P_{BS} increases the DL rates of the GUs, whereas a higher P_{GU} increases the UL rates of the GUs. The reason is that a higher P_{BS} allows more GUs to access the subchannels in the DL, and a higher P_{GU} allows the GUs to consume more power to communication.

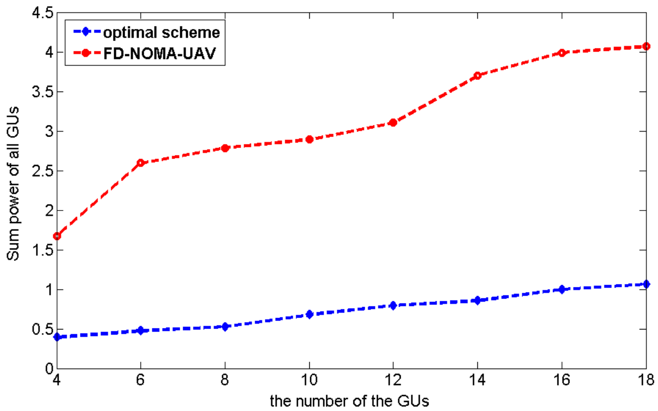

Fig. 11. Sum power of the GUs versus the number of CUs for different schemes.

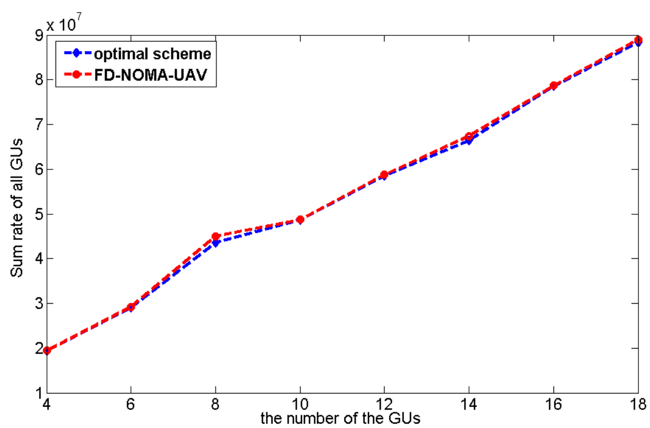

Fig. 12. Sum rate of the GUs versus the number of CUs for different power budgets.

Finally, the proposed FD-NOMA-UAV scheme is compared with the optimal scheme. In optimal scheme, the best pairs are chosen by the lowest consumed power.In Fig. 11 and Fig. 12, the sum power of the optimal scheme and FD-NOMA-UAV scheme are simulated. It can be observed that although the sum power of all GUs in FD-NOMA-UAV scheme is higher than that in optimal scheme, the sum rate of all GUs in FD-NOMA-UAV scheme is almost the same as that in optimal scheme. However,the biggest problem of the optimal scheme is that it costs too much time,and it can not work in a real scenario as the number of GUs increases.Therefore,the FD-NOMA-UAV scheme is more efficient than the optimal scheme.

VII. Conclusion

In this paper, we proposed a UL/DL transmission resource allocation method for UAV-aided FD-NOMA systems. The objective is to minimize the power requirements of the GUs while guaranteeing the users' QoS requirements. First, receiver determination of the users was performed using an access-priority method. Second, with the results of the receiver determination, the initial power of the GUs, the UAV, and the BS was determined. Third, based on the minimum sum of the UL transmission power, the users were paired by the Hungarian algorithm. Fourth, a UL/DL subchannel assignment method was proposed for the paired users, the UAV, and the BS. Finally, a soft access control scheme was presented based on the power budgets. Simulation results demonstrated the superiority of the FD-NOMA-UAV method over other methods regarding spectrum efficiency and energy efficiency. In future work, the effects of multi-UAV-aided FD-NOMA cells with imperfect SIC on resource allocation will be considered.

References

[1] X. You, C. Wang, J. Huang, X. Gao, and Z. Zhang, "Towards 6G wireless communication networks vision, enabling technologies, and new paradigm shifts," *Sci. China Inf. Sci.*, vol. 64, article number: 110301, 2021.

[2] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless challenges and opportunities," *IEEE J. Sel. Areas. Commun.*, vol. 32, no. 9, pp. 1637–1651, Sep. 2014.

[3] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," *IEEE VTC 2013-Spring*, June 2013.

[4] M. He and C. Huang, "Self-interference cancellation for full-duplex massive MIMO OFDM with single RF chain," *IEEE Wireless Commun. Lett.*, vol. 9, no. 1, pp. 26–29, Jan. 2020.

[5] S. Odajima, K. Murata, and N. Honma, "Optimal antenna arrangement for self-interference cancellation in short-range full-duplex MIMO," *Antennas Wirel. Propag. Lett.*, vol. 19, no. 9, pp. 1571–1575, Jul. 2020.

[6] M. Yilan, H. Ozkan, and O. Gurbuz, "Nonlinear digital self-interference cancellation with SVR for full duplex communication," in *IEEE WCNC*, 2020, pp.1–6.

[7] G. Gui, H. Sari, and E. Biglieri, "A new definition of fairness for non-orthogonal multiple access," *IEEE Communications Letters*, vol. 23, no. 7, pp. 1267–1271, Jul. 2019.

[8] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Communications Letters*, vol. 19, no. 8, pp. 1462–1465, Aug. 2015.

[9] M. S. Elbamby, M. Bennis, W. Saad, and M. Debbah, "Resource optimization and power allocation in in-band full duplex-enabled non-orthogonal multiple access networks," *IEEE J. Sel. Areas. Commun.*, vol. 35, no. 12, pp. 2860–2873, Dec. 2017.

[10] L. Wang, Y. Ai, N. Liu, and A. Fei, "User association and resource allocation in full-duplex relay aided NOMA systems," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10580–10596, Jun. 2019.

[11] F. Cheng, G. Gui, N. Zhao, Y. Chen, J. Tang, and H. Sari, "UAV-relaying-assisted secure transmission with caching," *IEEE Trans. Commun.*, vol. 67, no. 5, pp. 3140–3153, Mar. 2019.

[12] M. Mozaffari, W. Saad, M. Bennis, Y. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: applications, challenges, and open problems," *IEEE Commun. Surv. Tutor.*, vol. 21, no. 3, pp. 2334–2360, thirdquarter 2019.

[13] S. Ahmed, M. Z. Chowdhury, and Y. M. Jang, "Energy-efficient UAV relaying communications to serve ground nodes," *IEEE Commun. Lett.*, vol. 2, no. 4, pp. 849–852, Apr. 2020.

[14] T. Zhang, G. Liu, H. Zhang, W. Kang, G. K. Karagiannidis, and A. Nallanathan, "Energy-efficient resource allocation and trajectory design for UAV relaying systems," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6483–6498, Oct. 2020.

[15] R. Fan, J. Cui, S. Jin, K. Yang, and J. An, "Optimal node placement and resource allocation for UAV relaying network," *IEEE Commun. Lett.*, vol. 22, no. 4, pp. 808–811, Apr. 2018.

[16] Y. Wu, L. Qian, H. Mao, X. Yang, H. Zhou, and X. Shen, "Optimal power allocation and scheduling for non-orthogonal multiple access relay-assisted networks," *IEEE Trans. Mob. Comput.*, vol. 17, no. 11, pp. 2591–2606, Nov. 2018.

[17] M. F. Sohail, C. Y. Leow, and S. Won, "Energy-efficient non-orthogonal multiple access for UAV communication system," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 10834–10845, Nov. 2019.

[18] Y. Li, H. Zhang, K. Long, S. Choi, and A. Nallanathan, "Resource allocation for optimizing energy efficiency in NOMA-based fog UAV wireless networks," *IEEE Netw.*, vol. 34, no. 2, pp. 158–163, Feb. 2020.

[19] H. Wang, J. Wang, G. Ding, J. Chen, Y. Li, and Z. Han, "Spectrum sharing planning for full-duplex UAV relaying systems with underlaid D2D communications," *IEEE J. Sel. Areas. Commun.*, vol. 36, no. 9, pp. 1986–1999, Sep. 2018.

[20] M. Hua, L. Yang, C. Pan, A. Nallanathan, "Throughput maximization for full-duplex UAV aided small cell wireless systems," *IEEE Wireless Commun. Lett.*, vol. 9, no. 4, pp. 475–479, Apr. 2020.

[21] G. Mu, "Joint beamforming and power allocation for wireless powered UAV-assisted cooperative NOMA systems," *EURASIP J. Wireless Commun. and Netw.*, no. 1, pp. 1–14, Apr. 2020.

[22] Y. Xu, G. Gui, H. Gacanin, and F. Adachi, "A survey on resource allocation for 5G heterogeneous networks: Current research, future trends and challenges," *IEEE Commun. Surv. Tutor.*, vol. 23, no. 2, pp. 668–695, secondquarter 2021.

[23] D. DO,T. T. Nguyen, T. N. Nguyen, X. Li, and M. Voznak, "Uplink and downlink NOMA transmission using full-duplex UAV," *IEEE Access*, vol. 8, pp. 164347–164364, Sep. 2020.

[24] M. Liu, J. Yang, and G. Gui, "DSF-NOMA: UAV-assisted emergency communication technology in a heterogeneous internet of things," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5508–5519, Mar. 2019.

[25] M. Liu, N. Zhao, J. Sun, H. Gacanin, and H. Sari, "UAV-aided air-to-ground cooperative nonorthogonal multiple access," *IEEE Internet Things J.*, vol. 7, no. 4, pp. 2704–2715, Apr. 2020.

[26] Z. Xue, J. Wang, G. Ding, Q. Wu, Y. Lin, and T. A. Tsiftsis, "Device-to-device communications underlying UAV-supported social networking," *IEEE Access*, vol. 6, no. 6, pp. 34488–34502, Jun. 2018.

[27] M. Mozaffari,W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: performance and tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016.

[28] M. F. Sohail, C. Y. Leow and S. Won, "Non-orthogonal multiple access for unmanned aerial vehicle assisted communication," *IEEE Access*, vol. 6, no. 6, pp. 22716–22727, Jun. 2018.

[29] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, "Modeling air-to-ground path loss for low altitude platforms in urban environments," in *IEEE GLOBECOM*, pp. 2898–2904, 2014.

[30] 3GPP TS 25.105 V16.0.0 (2020-06): Base station (BS) radio transmission and reception (TDD) (Release 16). https://www.3gpp.org/ftp/Specs/2020-06/Rel-16/25_series/25105-g00.zip.

[31] H. W. Kuhn and Bryn Yaw, "The hungarian method for the assignment problem," *Naval Research Logistics Quarterly*, vol. 1-2, no. 2, pp. 83–97, Feb. 1955.

[32] M. Liu, and T. Song, "Deep cognitive perspective: resource allocation for NOMA-based heterogeneous IoT with imperfect SIC," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2885–2894, Feb. 2019.

[33] A. Abrardo, M. Belleschi, P. Detti, and M. Moretti, "Message passing resource allocation for the uplink of multi-carrier multi-format systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 130–141, Jan. 2012.

[34] N. Rupasinghe, Y. Yapici, I. Guvenc, and Y. Kakishima, "Non-orthogonal multiple access for mmWave drone networks with limited feedback," *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 762–777, Jan. 2019.

Wenjuan Shi (Member, IEEE) received the Ph.D. degree in Information and Communication Engineering from China University of Mining and Technology, in 2019. Since 2017, she is an associate professor in in the school of Physics and Electronic Engineering,Yancheng Teachers University. Her current research interests include wireless communication, video quality assessment and image processing.

Yanjing Sun (Member, IEEE) received the Ph.D. degree in Information and Communication Engineering from China University of Mining and Technology in 2008. He is a professor in School of Information and Control Engineering, China University of Mining and Technology since July 2012. His current research interests include wireless communication, the Internet of Things, embedded real-time system, wireless sensor networks, and cyber-physical system.

Miao Liu (Member, IEEE) received the Ph.D. degree in communication engineering from Southeast University, Nanjing, China in 2019. He is an assistant professor with Nanjing University of Posts and Telecommunications, Nanjing China.

Hu Xu (Member, IEEE) received Ph.D. degree Nanjing University of Posts and Telecommunications in 2007 in China. Currently, he is a professor in the school of Physics and Electronic Engineering, Yancheng Teachers University, China. His current research interests include LDPC codes design, compressed sensing and magnetic induction communication and so on.

Guan Gui (Senior Member, IEEE) received the Dr. Eng degree in Information and Communication Engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2012. Since 2015, he has been a professor with Nanjing University of Posts and Telecommunications (NJUPT), Nanjing, China. His recent research interests include artificial intelligence, deep learning, non-orthogonal multiple access, wireless power transfer, and physical layer security.

Tomoaki Ohtsuki (Senior Member, IEEE) eceived the B.E., M.E., and Ph. D. degrees in Electrical Engineering from Keio University, Yokohama, Japan in 1990, 1992, and 1994, respectively. He is now a Professor at Keio University. He is engaged in research on wireless communications, optical communications, signal processing, and information theory.

Bamidele Adebisi (Senior Member, IEEE) received the Dr. Eng degree in Information and Communication Engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2012. Since 2015, he has been a professor with Nanjing University of Posts and Telecommunications (NJUPT), Nanjing, China. His recent research interests include artificial intelligence, deep learning, non-orthogonal multiple access, wireless power transfer, and physical layer security.

Haris Gacanin (Fellow, IEEE) received MSc and Ph.D. from Tohoku University, Japan, in 2005 and 2008, respectively. He is a head of the Chair for Distributed Signal Processing and co-director of the Institute for Communication Technologies and Embedded Systems. His professional interests are related to broad areas of digital signal processing and artificial intelligence with applications in wireless communications.

Fumiyuki Adachi (Life Fellow, IEEE) received the Dr. Eng degree in Information and Communication Engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2012. Since 2015, he has been a professor with Nanjing University of Posts and Telecommunications (NJUPT), Nanjing, China. His recent research interests include artificial intelligence, deep learning, non-orthogonal multiple access, wireless power transfer, and physical layer security.